PB80-188824

Lime FGD Systems Data Book

PEDCo-Environmental, Inc.
Cincinnati, OH

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Apr 79

U.S. Department of Commerce
National Technical Information Service
NTIS

EPA

U.S. Environmental
Protection Agency
Office of Research
and Development

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

EPA-600/8-79-009
April 1979

EPRI

Electric Power
Research Institute

3412 Hillview Avenue
Palo Alto CA 94303

P/N 3283

PB80-188824

Lime FGD Systems Data Book

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

727

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the SPECIAL REPORTS series. This series is reserved for reports which are intended to meet the technical information needs of specifically targeted user groups. Reports in this series include Problem Oriented Reports, Research Application Reports, and Executive Summary Documents. Typical of these reports include state-of-the-art analyses, technology assessments, reports on the results of major research and development efforts, design manuals, and user manuals.

EPA REVIEW NOTICE

This report has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/8-79-009

2.

3. RECIPIENT'S ACCESSION NO.
PB 80-188824

4. TITLE AND SUBTITLE
Lime FGD Systems Data Book

5. REPORT DATE
April 1979

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) T. C. Ponder Jr., J. S. Hartman, H. M. Drake, R. P. Kleir, J. S. Master, A. N. Patkar, R. D. Tems, and J. D. Tuttle

8. PERFORMING ORGANIZATION REPORT NO.
P/N 3283

9. PERFORMING ORGANIZATION NAME AND ADDRESS
PEDCo Environmental, Inc.
11499 Chester Road
Cincinnati, Ohio 45246

10. PROGRAM ELEMENT NO.
EHE624A

11. CONTRACT/GRANT NO.
68-02-2603, Tasks 5 and 35

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Research and Development*
Industrial Environmental Research Laboratory
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED
Task Final; 12/76 - 12/78

14. SPONSORING AGENCY CODE
EPA/600/13

15. SUPPLEMENTARY NOTES (*) Cosponsored by Electric Power Research Institute, 3412 Hillview Ave., Palo Alto CA 94303. Project officers: W. D. Peters (IERL-RTP, 919/541-2547) and T. A. Morasky (EPRI, 415/855-2468). (R. Stern is IERL-RTP Acting P.O.)

16. ABSTRACT
The Data Book is intended to aid engineers in understanding the process design features that are unique to lime flue gas desulfurization (FGD) systems. It is intended to supplement, not replace, basic information on engineering design. It is addressed to engineers who must design, evaluate, or operate lime FGD systems. The information may also be useful to persons who are familiar with utility operations, but unfamiliar with chemical operations. The Data Book covers the entire process of lime-based FGD. The gas-side battery limits extend from the discharge of the steam generator to the discharge of the stacks. The absorbent-side battery limits extend from receipt of the lime to sludge discharge to the final sludge disposal site.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Boilers	Air Pollution Control	13B	13A
Combustion	Calcium Oxides	Stationary Sources	21B	
Sulfur Dioxide	Gas Scrubbing	Utility Boilers	07B	13H
Flue Gases		Lime		
Scrubbers		FGD Systems	07A,13I	
Desulfurization		Alkali Scrubbing	07D	
Mist		Mist Eliminators	04B	

18. DISTRIBUTION STATEMENT
Unlimited

19. SECURITY CLASS *(This Report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES
724

22. PRICE

EPA Form 2220-1 (9-73)

EPA-600/8-79-009
April 1979

Lime FGD Systems Data Book

by

T.C. Ponder Jr., J.S. Hartman, H.M. Drake, R.P. Kleir,
J.S. Master, A.N. Patkar, R.D. Tems, and J.D. Tuttle

PEDCo Environmental, Inc.
11499 Chester Road
Cincinnati, Ohio 45246

Contract No. 68-02-2603
Tasks No. 5 and 35
Program Element No. EHE624A

EPA Project Officer: Warren D. Peters

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

EPRI Project Officer: Thomas A. Morasky

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

PREFACE

To date, lime-based FGD systems account for approximately 11,000 of the 28,000 MW of FGD capacity installed or under construction. As a result, a large information base is becoming available, but up to now it has not been compiled in a format that is readily accessible and usable by the utility industry. The Lime FGD Systems Data book should permit a utility to anticipate the performance, reliability, and maintenance characteristics of alternative lime scrubbing system designs available, as a function of site-specific variables. This information should improve the quality of bid specifications as well as the ability to judge the merit of alternative lime scrubbing system proposals.

The objective of the Lime FGD Systems Data Book is to provide the utility industry with 1) detailed guidelines about design features, equipment specifications and selection criteria of lime scrubbers, and 2) specific procedures to determine which system design parameters are critical in confidently selecting a lime slurry system. The book is designed to enable a utility engineer to predict and/or specify scrubber system parameters such as energy requirements, equipment and vessel sizes, system efficiencies, equipment and subsystem redundancy needs, scrubber waste characteristics, fresh water makeup, maintenance requirements, and system costs. Proper implementation of the information in this manual will result in scrubbing systems having increased reliability and decreased maintenance needs. In addition, the Data Book describes the process chemistry involved in lime scrubbing and highlights the interrelationship of process chemistry with the proper selection of system components. It is essential to understand this relationship to apply a logical chemical engineering approach when integrating a lime scrubbing process into a utility boiler system.

CONTENTS

Page
Preface ii
List of Tables v
List of Figures xii
Conversions xix
Abbreviations xxi
Acknowledgements xxiv

1.0 Introduction

1.1 General 1.1-1
1.2 Project Purpose and Scope 1.2-1
1.3 Description of Contents 1.3-1

2.0 Process Design

2.1 Introduction 2.1-1
2.2 Effects of Design Parameters on Process Design 2.2-1
2.3 Procedures for Calculating a Material Balance 2.3-1
2.4 Sludge Disposal 2.4-1

3.0 Process Control

3.1 Introduction 3.1-1
3.2 Practical Applications of Process Control 3.2-1
3.3 Lime Scrubber Control Subsystems 3.3-1
3.4 Basic Control Hardware 3.4-1

4.0 Equipment Design

4.1 Introduction 4.1-1
4.2 Recirculating Pumps 4.2-1
4.3 Other Process Pumps 4.3-1
4.4 Lime Unloading and Storage 4.4-1
4.5 Slurry Preparation 4.5-1
4.6 Scrubber/Absorber 4.6-1
4.7 Mist Eliminator 4.7-1
4.8 Fans 4.8-1
4.9 Thickener/Clarifier 4.9-1
4.10 Mechanical Dewatering Equipment 4.10-1
4.11 Reheaters 4.11-1
4.12 Corrosion 4.12-1
4.13 Instrumentation 4.13-1

CONTENTS (continued)

Page

5.0 Bid Request/Evaluation

5.1 Introduction 5.1-1
5.2 Design Basis 5.2-1
5.3 Guarantee Requests 5.3-1
5.4 Equipment and Instrumentation Summary 5.4-1
5.5 Bid Evaluation 5.5-1

Glossary G-1

LIST OF TABLES

Table		Page
2.2-1	Factors That Influence Scrubber System Design Outside the Battery Limits	2.2-2
2.2-2	Factors That Influence Scrubber System Design Inside the Battery Limits	2.2-3
2.2-3	Typical Analysis of Representative U.S. Coals As Received	2.2-4
2.2-4	Average Ash Constituents of Three Ranks of Coal	2.2-12
2.2-5	Ash Analyses of Selected Coals	2.2-13
2.2-6	Constituents and Properties of Selected Coals	2.2-16
2.2-7	Composition of Various Grades of U.S. Coals	2.2-17
2.2-8	Classification of Coal by Rank	2.2-18
2.2-9	Coal Analyses and Sulfur Variability Over Various Averaging Times	2.2-19
2.2-10	Process Approximations	2.2-51
2.3-1	Enthalpies of Various Gases	2.3-2
2.3-2	Molecular Weights Frequently Used in Material Balance Calculations	2.3-3
2.3-3	Energy Requirement Calculations	2.3-4
2.3-4	Design Information	2.3-17
2.3-5	Typical Pressure Drop Data	2.3-18
2.3-6	Lime Analysis	2.3-18
2.3-7	Composition of the Available Lime for SO_2 Absorption	2.3-42
2.3-8	Waste Slurry Suspended Solids	2.3-48
2.3-9	Inlet Flue Gas to Scrubber (Stream 6)	2.3-49
2.3-10	Cleaned Flue Gas Composition (Stream 7)	2.3-53

LIST OF TABLES (Continued)

Table | | Page
2.3-11 Design Boiler and Fuel Data for Bruce Mansfield Nos. 1,2, and 3 .... 2.3-59

2.3-12 Bruce Mansfield Scrubber and Absorber Data 2.3-62

2.3-13 Boiler and Fuel Data, Came Run No. 4 .... 2.3-64

2.3-14 Pertinent Boiler and Fuel Data for Conesville No. 5 .... 2.3-67

2.3-15 Material Balance for Conesville No. 5 .... 2.3-70

2.3-16 FGD Tank Information for Conesville No. 5 .... 2.3-72

2.3-17 Pertinent Boiler Data, Green River Plant 2.3-74

2.3-18 Fuel Data, Green River Plant 2.3-74

2.3-19 Green River Scrubber Data 2.3-77

2.3-20 Reaction Tank Data, Green River Plant 2.3-79

2.3-21 Makeup Water Requirements, Green River Plant 2.3-79

2.3-22 Boiler Data for Unit 6, Paddy's Run Station 2.3-81

2.3-23 Fuel Data for Unit 6, Paddy's Run Station 2.3-81

2.3-24 Absorber Data, Paddy's Run 2.3-83

2.3-25 Carbide Lime Analysis, Paddy's Run 2.3-84

2.3-26 FGD Tank Data, Paddy's Run 2.3-85

2.3-27 Thickener and Vaccuum Filter Data, Paddy's Run 2.3-86

2.3-28 Water Requirement, Paddy's Run 2.3-87

2.3-29 Boiler Data, Phillips Power Station 2.3-88

2.3-30 Phillips Power Scrubber Data for Particulate and FGD Scrubber Modules 2.3-89

2.3-31 Conversion Factors 2.3-92

2.4-1 Lime FGD Systems that Fixate Sludge 2.4-5

2.4-2 Flue-Gas-Cleaning and Sludge Disposal Practices for Utility Scrubbers Using Throwaway Processes and Operational on November 1, 1977 .... 2.4-17

LIST OF TABLES (Continued)

Table Page

2.4-4 Summary of the Revenue Requirements During the 30-Year Life of a New Power Plant for Various FGD Waste Disposal Methods 2.4-22

3.4-1 Recommended Control Modes 3.4-5

4.2-1 Survey of Vendor Pump Specifications 4.2-14

4.2-2 Slurry recirculation Pumps Malfunctions and Causes 4.2-16

4.2-3 Scrubber slurry recirculation pump specifications-- Existing Facilities 4.2-17

4.3-1 Lime FGD Systems Pump Data--Lime Slurry Feed Pumps 4.3-2

4.3-2 Lime Scrubber Pump Data Thickener Supernatant Pumps 4.3-2

4.3-3 Lime Scrubber Pump Data--Thickener Underflow Pumps 4.3-7

4.4-1 Standard Sizes of Quicklime 4.4-2

4.4-2 Physical properties of Quicklime 4.4-4

4.4-3 Covered or Hopper Barges 4.4-10

4.4-4 Existing Facility Design Specifications 4.4-24

4.5-1 Characteristics of Detention and Paste Slakers 4.5-15

4.5-2 Operating Characteristics of Lime Slaking Facilities ... 4.5-19

4.5-3 Approximate Agitator Motor Horsepower Required for Lime Suspension 4.5-22

4.5-4 Stabilization and Storage Systems 4.5-25

4.6-1 SO_2 Absorbers in Operational Lime FGD Systems 4.6-2

4.6-2 Venturi Throat Corrosion Spool Test Data 4.6-6

4.6-3 Scrubber Corrosion Spool Test Data Below and Above the Mist Eliminator 4.6-7

4.6-4 Conditions for the Corrosion Tests at the Shawnee Station of TVA 4.6-8

4.6-5 Chemical Analysis of Alloys 4.6-9

LIST OF TABLES (Continued)

Tables		Page
4.6-6	Typical Characteristics of Furan Resins	4.6-11
4.6-7	Typical Characteristics of Epoxy Resins	4.6-12
4.6-8	Typical Characteristics of Vinyl Ester Resins	4.6-13
4.6-9	Typical Characteristics of Polyester Resins	4.6-14
4.6-10	Property Characteristics for Natural Rubber and Neoprene Rubber	4.6-16
4.6-11	Properties of Type "H" and "L" Bricks	4.6-18
4.6-12	Summary of Operating Lime FGD Systems as of January 1978	4.6-34
4.9-1	Chemical Analysis of the Sludge of a Lime-Scrubbing System	4.9-6
4.9-2	Typical Size Distribution of a Lime-Generated Sludge ...	4.9-18
4.9-3	Summary of the Characteristic Differences Between the Two Classes of Colloids	4.9-19
4.9-4	Existing Thickener Facilities for Lime Scrubbing FGD System	4.9-30
4.11-1	Survey of In-Line Reheat System	4.11-25
4.11-2	Survey of Direct-Fired Reheat System	4.11-26
4.12-1	Corrosion of Reheater Tubes from Colbert Pilot Plant After 3800 Hours	4.12-14
4.13-2	pH Control Instrumentation	4.13-6
4.13-3	Solids Content Instrumentation	4.13-8
4.13-4	SO_2 Instrumentation	4.13-11
4.13-5	Liquid Level Instrumentation	4.13-17
4.13-6	Flow Instrumentation	4.13-24
5.4-1a	EPRI Lime FGD Systems Data Book Equipment List	5.4-2
5.4-2	EPRI Lime FGD System Data Book Venturi Scrubber Specifications	5.4-4

LIST OF TABLES (Continued)

Tables		Page
5.4-3	EPRI Lime FGD System Data Book Venturi Recirculation Pump Specifications	5.4-6
5.4-4	EPRI Lime FGD System Data Book Venturi Recirculation Tank Specifications	5.4-8
5.4-5	EPRI Lime FGD System Data Book Presaturator Specifications	5.4-9
5.4-6	EPRI Lime FGD Systme Data Book Absorber Specifications	5.4-12
5.4-7a	EPRI Lime FGD System Data Book Reaction Tank Pump Specifications	5.4-14
5.4-7b	EPRI Lime FGD System Data Book Absorber Recirculation Pump Specifications	5.4-15
5.4-8	EPRI Lime FGD System Data Book Absorber Recirculation Tank Specifications	5.4-17
5.4-9	EPRI Lime FGD Systems Data Book Mist Eliminator	5.4-19
5.4-10	EPRI Lime FGD System Data Book Centrifugal Compressor Specifications	5.4-22
5.4-11	EPRI Lime FGD System Data Book Damper Specifications	5.4-24
5.4-12	EPRI Lime FGD System Data Book Duct Work Specifications	5.4-26
5.4-13	EPRI Lime FGD System Data Book Booster Fan Specifications	5.4-28
5.4-14	EPRI Lime FGD System Data Book Belt Conveyor Specifications	5.4-30
5.4-15	EPRI Lime FGD System Data Book Slaker Specifications	5.4-32
5.4-16	EPRI Lime FGD System Data Book Lime Stabilization/ Storage Tank Specifications	5.4-34
5.4-17	EPRI Lime FGD System Data Book Lime Slurry Pump Specifications	5.4-35
5.4-18	EPRI Lime FGD System Data Book Freshwater Pump Specifications	5.4-37
5.4-19	EPRI Lime FGD System Data Book Thickener Specifications	5.4-39

LIST OF TABLES (Continued)

Table		Page
5.4-20	EPRI Lime FGD System Data Book Flocculant Proportioning Pump Specifications	5.4-41
5.4-21	EPRI Lime FGD System Data Book Thickener Underflow Pump Specifications	5.4-42
5.4-22	EPRI Lime FGD System Data Book Thickener Overflow Pump Specifications	5.4-44
5.4-23	EPRI Lime FGD System Data Book Thickener Overflow Tank Specifications	5.4-45
5.4-24	EPRI Lime FGD System Data Book Centrifugal Separator Specifications	5.4-47
5.4-25	EPRI Lime FGD System Data Book Vacuum Filter Specifications	5.4-49
5.4-26	EPRI Lime FGD System Data Book Filtrate or Centrate Pump Specifications	5.4-51
5.4-27	EPRI Lime FGD System Data Book Fixation Tank Specifications	5.4-53
5.4-28	EPRI Lime FGD System Data Book Sludge Disposal Specifications	5.4-55
5.4-29	EPRI Lime FGD System Data Book Belt Conveyor Specifications	5.4-57
5.4-30	EPRI Lime FGD System Data Book Screw Conveyor Specifications	5.4-59
5.4-31	EPRI Lime FGD System Data Book Pond Water Return Pump Specifications	5.4-60
5.4-32	EPRI Lime FGD System Data Book pH Instruments Specifications	5.4-63
5.4-33	EPRI Lime FGD System Data Book Liquid Level Indicator Specifications	5.4-65
5.4-34	EPRI Lime FGD System Data Book Flowmeter Specifications	5.4-68
5.4-35	EPRI Lime FGD System Data Book SO_2 Analyzer Specifications	5.4-70

LIST OF TABLES (Continued)

Table		Page
5.4-36	EPRI Lime FGD System Data Book Pressure Sensors Specifications	5.4-71
5.4-37	EPRI Lime FGD System Data Book Temperature Sensors and Controllers Specifications	5.4-73
5.4-74	EPRI Lime FGD System Data Book Control Valve Specifications	5.4-74
5.5-1	Bid Evaluation for Slakers	5.5-2
5.5-2	Lime Slurry Pump	5.5-3
5.5-3	Bid Evaluation for SO_2 Absorber	5.5-4
5.5-4	Bid Evaluation for Mist Eliminatory	5.5-5
5.5-5	Bid Evaluation for Reheater	5.5-6
5.5-6	Bid Evaluation for Booster Fan	5.5-7
5.5-7	Bid Evaluation for Recirculation Tank	5.5-8
5.5-8	Bid Evaluation for Thickener	5.5-9

LIST OF FIGURES

Figure		Page
2.3-1	Additive vs. outlet requirements	2.3-5
2.3-2	Horsepower vs. outlet requirements	2.3-6
2.3-3	Recirculation pump energy requirement	2.3-7
2.3-4	Fan energy requirement	2.3-8
2.3-5	Reheat energy requirement	2.3-9
2.3-6	Psychrometric chart	2.3-10
2.3-7	SO_2 emission calculation	2.3-11
2.3-8	Lime requirement calculation	2.3-12
2.3-9	Saturated gas calculation	2.3-13
2.3-10	Recirculation tank capacity calculation	2.3-14
2.3-11	Wet sludge calculation	2.3-15
2.3-12	500-MW model plant for example 1	2.3-16
2.3-13	Overall material balance	2.3-22
2.3-14	Boiler-furnace material balance	2.3-23
2.3-15	SO_2 and particulate balance	2.3-24
2.3-16	Scrubber material balance	2.3-26
2.3-17	Detailed boiler-furnace material balance	2.3-27
2.3-18	Summary of SO_2 and particulate material balance	2.3-41
2.3-19	Summary of slurry preparation material balance	2.3-46
2.3-20	Pond material balance	2.3-48
2.3-21	Psychometric chart for example 1	2.3-52
2.3-22	Summary of scrubber material balance	2.3-56
2.3-23	Water balance summary	2.3-58
2.3-24	Simplified flow diagram of Bruce Mansfield	2.3-60

LIST OF FIGURES (Continued)

Figure | Page

2.3-25 Flow diagram of Cane Run No. 4 .... 2.3-65

2.3-26 Flow diagram of Conesville No. 4 .... 2.3-69

2.3-27 Flow diagram of Green River Station 2.3-76

2.3-28 Flow diagram of Paddy's Run 2.3-82

2.3-29 Flow diagram of the dual-stage scrubber train at Phillips 2.3-90

3.2-1 Feedback control loop in a stack gas reheat control system 3.2-2

3.2-2 Improved feedback control in stack gas reheat control system 3.2-5

3.2-3 Cascade control 3.2-6

3.2-4 Feed-forward control 3.2-8

3.2-5 Lime scrubber control system 3.2-11

3.3-1 Fuel-fired reheat control system 3.3-2

3.3-2a Hot water reheat control system: steam raises hot water temperature 3.3-4

3.3-2b Hot water reheat control system: flow of water charged by temperature controller 3.3-5

3.3-3 Shape of neutralization curve 3.3-7

3.3-4 Simple pH control 3.3-9

3.3-5 Cascade pH control 3.3-11

3.3-6 Outlet SO_2 feedback control (limited) 3.3-13

3.3-7 Inlet SO_2 feed-forward control 3.3-14

3.3-8 Lime slurry solids content: density feedback 3.3-16

3.3-9 Lime slurry solids content: feed-forward control 3.3-17

3.3-10 Absorber solids content: thickener bleed control 3.3-19

3.3-11 Absorber solids content: thickener bleed control 3.3-20

LIST OF FIGURES (Continued)

Figure		Page
3.3-12	Thickener solids content: underflow control flow	3.3-21
3.3-13	Thickener solids content: recycle control	3.3-21
3.3-14	Thickener solids content: flocculant control	3.3-23
3.3-15	Absorber: thickener solids control system	3.3-24
3.3-16	Simple pressure control	3.3-26
3.3-17	Basic fan control subsystem	3.3-27
3.3-18	Module load balancing control	3.3-28
3.3-19	Flue gas flow: fan control	3.3-30
3.4-1	Theoretical controller response curves	3.4-4
3.4-2	Valve characteristics	3.4-7
4.2-2	Slurry recirculation pump detail assembly	4.2-3
4.2-3	Specific gravity of scrubber recirculation slurry	4.2-6
4.2-4	Types of impellers for recirculation pumps	4.2-9
4.2-5	Pump seal water flow	4.2-11
4.4-1	The angle of repose	4.4-4
4.4-2	Pressure-differential tank trailer	4.4-7
4.4-3	Hopper trailer with air-activated gravity discharge hopper	4.4-9
4.4-4	Covered hopper car	4.4-9
4.4-5	Vacuum barge unloading	4.4-11
4.4-6	Blower truck receiving bin	4.4-13
4.4-7	Vacuum railcar unloading	4.4-15
4.4-8	Mechanical conveyors	4.4-17
4.4-9	Positive-pressure pneumatic conveyor	4.4-18
4.4-10	Closed-loop pneumatic system	4.4-20

LIST OF FIGURES (Continued)

Figure Page

4.4-11 Feed bin design 4.4-23

4.5-1 Lime slurry system--schematic flow 4.5-2

4.5-2 Volumetric belt-type feeder 4.5-4

4.5-3 Oscillating hopper volumetric feeder 4.5-5

4.5-4 Mechanical gravimetric feeder 4.5-7

4.5-5 Gravimetric feeder 4.5-9

4.5-6 Detention slaker 4.5-13

4.5-7 Paste slaker 4.5-14

4.5-8 Typical stabilization tank (simplified) 4.5-21

4.5-9 Agitator baffle design 4.5-24

4.5-10 Bruce Mansfield stabilization and storage 4.5-26

4.5-11 Conesville stabilization and storage 4.5-27

4.5-12 Phillips stabilization and storage 4.5-29

4.5-13 Green River slaking and stabilization system 4.5-30

4.7-1a Discontinuous horizontal chevron zigzag baffle 4.7-4

4.7-1b Continuous horizontal chevron zigzag baffle 4.7-4

4.7-2 The chevron impingement principle 4.7-5

4.7-3 Heil chevron mist eliminator 4.7-6

4.7-4 Heil chevron mist eliminator performance 4.7-7

4.7-5 Verticle configuration of Humboldt Lamellar separator in horizontal duct (looking downward) marketed by Matsuzaka 4.7-8

4.7-6 Munters euroform mist eliminator 4.7-11

4.7-7 Radial-vane mist eliminator 4.7-12

4.7-8 Mist eliminator designs showing the difference in baffling angle and the number of passes 4.7-15

LIST OF FIGURES (Continued)

Figure		Page
4.7-9	Schematic of two-, three-, and six-pass chevron mist eliminators	4.7-16
4.7-10	Slanted mist eliminator for vertical gas flow	4.7-17
4.7-11	Cross section of mist eliminator with special reentrainment-prevention features	4.7-19
4.7-12	Horizontal and vertical mist eliminators	4.7-21
4.7-13	Bulk separation systems	4.7-23
4.7-14	Koch flexitray wash tray	4.7-24
4.7-15	UOP trap-out tray	4.7-25
4.7-16	Droplet sizing photograph	4.7-31
4.7-17	Percent removal vs. mist droplet diameter obtained by the application of the CFH method	4.7-32
4.8-1	Scrubber FD fan application	4.8-3
4.8-2	ID fan application	4.8-4
4.8-3	Wet fan application	4.8-7
4.9-1	Sequence of sedimentation in a cylinder	4.9-2
4.9-2	Thickener supported by a center column, with truss-type rake arms and Thixo post plow blades	4.9-4
4.9-3	Hinged rod-type designs with two types of support structure	4.9-5
4.9-4	Calcium sulfite sludge	4.9-7
4.9-5	Calcium sulfate sludge	4.9-7
4.9-6	Center drive unit (EIMCO)	4.9-10
4.9-7	Plow blade designs shown with truss-type rake arms	4.9-13
4.9-8	Positive lifting device used on column-supported thickeners	4.9-15
4.9-9	Standard tunnel system	4.9-16

LIST OF FIGURES (Continued)

Figure Page

4.9-10 Underflow pumping arrangements through center column 4.9-17

4.9-11 Effect of polymer on settling rate of lime-generated sludge 4.9-21

4.9-12 Typical automatic dry polymer feed system 4.9-23

4.9-13 Graphical analysis of interface settling curve 4.9-26

4.9-14 EIMCO swinglift thickener at Cane Run Power Station 4.9-32

4.9-15 Dorr-Oliver cable torq thickener at Conesville Power Station 4.9-34

4.10-1 Solid bowl centrifuge 4.10-2

4.10-2 Cutaway view of a rotary-drum vacuum filter 4.10-9

4.10-3 Operating zones of vacuum filters 4.10-10

4.10-4 Flow sheet for continuous rotary-drum vacuum filtration.. 4.10-11

4.10-5 Drum and internal piping 4.10-13

4.10-6 Filtration rate vs. feed solids 4.10-17

4.10-7 Dry cake rate vs. cycle time 4.10-17

4.10-8 Filter leaf test apparatus 4.10-21

4.10-9 Cross section of a belt filter 4.10-24

4.10-10 Filter costs 4.10-25

4.10-11 Pox-O-Tec process 4.10-27

4.11-1 Reheat system location 4.11-2

4.11-2 In-line reheat system 4.11-5

4.11-3a Direct-firing reheat system using in-line burner 4.11-7

4.11-3b Direct-firing reheat system using external combustion chamber 4.11-7

4.11-4 Indirect hot air reheat system 4.11-9

LIST OF FIGURES (Continued)

Figure		Page
4.11-5	Bypass reheat system	4.11-10
4.11-6	Reheat by exit gas recirculation	4.11-10
4.11-7	Schematic of heat balance around downstream system with indirect hot air reheater	4.11-12
4.11-8	Schematic of heat balance around downstream system with indirect hot air reheater	4.11-14
4.11-9	Schematic of heat balance around downstream system with direct combustion reheater	4.11-16
4.11-10	Effect of reheat temperature (for in-line reheat) on ground level SO_2 concentration at various scrubber efficiencies	4.11-20
4.12-1	Continuous weld and series of spot welds	4.12-9
4.12-2	EB insert ring, consumable flat ring, and standard backing ring	4.12-10
4.12-3	Double butt weld, single fillet lap weld, and double fillet lap weld	4.12-11
4.12-4	Examples of good and bad finishing techniques for welds	4.12-12
4.12-5	Complete full weld	4.12-13
4.13-1	Ideal SO_2 sampling system	4.13-10
4.13-2	Displacement level instrument control system	4.13-13
4.13-3	Flange-mounted differential-pressure level control system	4.13-15
4.13-4	Quadrant-edged orifice plate	4.13-20
4.13-5	Typical magnetic flow meter	4.13-21

CONVERSIONS

The U.S. Environmental Protection Agency policy is to express all measurements in metric units. Generally, however, this report uses British units of measure which are still commonly used in the industry. For conversion to the metric system, use the following conversions:

To convert from	To	Multiply by
°C*	°F	1.8 (°C) + 32
°F	°C	0.556 (°F-32)
Btu	J	1.055 E + 03[†]
Btu/scf (70°F)	MJ/Nm^3 (0°C)	4.011 E - 02
Btu/lb	kJ/kg	2.326 E + 00
ft	m	3.048 E - 01
ft^2	m^2	9.290 E - 02
ft^2/1000 acfm	m^2/(m^3/s)	1.968 E - 01
ft^2	m^3	2.832 E - 02
acfm	m^3/h	1.699 E + 00
scfm	Nm^3/s	4.383 E - 04
gal	liter	3.785 E + 00
gpm/ft^2	l/min/m^2	4.080 E + 01
m^3	liter	1.000 E + 03
gal/1000 scf	liter/m^3	1.337 E - 01

CONVERSIONS (continued)

To convert from	To	Multiply by
gr	g	6.480 E - 02
gr/ft^3	g/m^3	2.288 E + 00
gr/scf	g/Nm^3	2.464 E + 00
hp	kW	7.457 E - 01
in. W. G.	Pa	2.491 E + 02
lb	kg	4.536 E - 01
lb moles/hr	g moles/min	7.560 E + 00
lb/10^6 Btu	g/mJ	4.298 E - 01
lb/ft^3	kg/m^3	1.602 E + 01
psi	Pa	6.895 E + 03
ton	Mg	9.072 E - 01
W/ft^2	W/m^2	1.076 E + 01
Metric prefixes	giga (G) 10^9	
	mega (M) 10^6	
	kilo (k) 10^3	
	centi (c) 10^{-2}	
	milli (m) 10^{-3}	
	nano (n) 10^{-9}	

* Abbreviations given on pages ix through xi.

† E indicates the power of 10 by which the conversion factor must be multiplied to obtain the correct value.

ABBREVIATIONS

Symbol	Unit
°C	degree Celsius
°F	degree Fahrenheit
acfm	actual cubic foot per minute
Btu	British thermal unit
Btu/scf	British thermal unit per standard cubic foot
Btu/lb	British thermal unit per pound
ft	foot
ft^2	square foot
ft^2/1000 acfm	square foot per one thousand cubic feet per minute
ft^3	cubic foot
gal	gallon
gpm	gallons per minute
gal/1000 scfm	gallon per one thousand standard cubic feet
gpm/ft^2	gallons per minute per square foot
gr	grain
gr/scf	grain per standard cubic foot
gr/ft^3	grain per cubic foot
g	gram

ABBREVIATIONS (continued)

Symbol	Unit
g-moles	gram moles
h	hour
hp	horsepower
in.	inches
in. W. G.	inch Water Gage
J	joule
kJ/kg	kilojoule per kilogram
kW	kilowatt
lb	pound
lb/10^6 Btu	pound per million British thermal units
lb/ft^3	pound per cubic foot
lb-moles	pound moles
lb-moles/h	pound moles per hour
lb-moles/min	pound moles per minute
m^2	square meter
m^3	cubic meter
mg	milligram
MJ/Nm^3	megajoule per normal cubic meter
ng	nanogram
Nm^3/s	normal cubic meter per second
Pa	pascal
ppm	parts per million

ABBREVIATIONS (continued)

Symbol	Unit
psi	pound per square inch
s	second
scfm	standard cubic foot per minute
W/ft^2	watt per square foot

ACKNOWLEDGEMENTS

This report has been jointly sponsored by the Electric Power Research Institute (EPRI), Palo Alto, California, and the U.S. Environmental Protection Agency (EPA), Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina.

This report represents the combined efforts of many individuals. It is impractical to express appreciation to every contributor who aided in the compilation of data for this book. The authors, however, do wish to acknowledge the advice and assistance of Thomas M. Morasky, the EPRI Project Manager, and Warren D. Peters and J. David Mobley, the EPA Project Officers. A. V. Slack and Dr. P. S. Lowell also reviewed and contributed their expertise to this document. The authors would also like to acknowledge the valuable assistance of the EPRI review committee, who so graciously contributed their time and effort.

Mr. Timothy W. Devitt and Mr. Thomas C. Ponder, Jr., served as Project Directors for PEDCo Environmental, Inc., and Mr. Russell P. Kleir and Mr. J. Scott Hartman served as Project Managers.

Additionally, the assistance of several PEDCo Environmental personnel aided in the completion of the book; they are H. M. Drake, Dr. K. W. Hahn, M. P. Hartman, S. P. Kothari, J. S. Master, A. N. Patkar, R. R. McKibben, R. D. Tems, and J. D. Tuttle.

Finally, the authors wish to acknowledge the help afforded by a great number of process and equipment suppliers, whose assistance aided in the completeness of the text.

SECTION 1

INTRODUCTION

1.1 GENERAL

This data book represents the joint effort of the Electric Power Research Institute and U.S. Environmental Protection Agency. The project was initiated under fundings from the EPA Industrial Environmental Research Laboratory (IERL), Research Triangle Park, North Carolina, and the Electric Power Research Institute (EPRI), Palo Alto, California as part of the Technology Transfer Program. This book is an assemblage of current data on lime flue gas desulfurization (FGD) technology.

This manual serves to integrate and summarize the results of extensive utility, architect-engineer, vendor, EPA, and EPRI efforts in the development of lime scrubbing technology. Much of the information contained herein is derived from the results of research projects funded by EPRI and EPA. During the compilation of this manual, review and suggestions regarding the technical content of this manual were provided by an advisory committee that consisted of representatives from the utilities, Edison Electric Institute's Prime Movers Committee, architect-engineering firms, and the EPA.

1.2 PROJECT PURPOSE AND SCOPE

The Data Book was written as an aid to utility engineers involved in the design, specification, project management, and operation of lime-based flue gas desulfurization (FGD) systems. The information is aimed at technical personnel who already have knowledge of utility power plant operations but may not be familiar with the chemical processes and equipment that comprise FGD systems.

The scope of the Data Book is the entire process of lime-based flue gas desulfurization. The gas-side battery limits extend from the discharge of the steam generator to the discharge of the stacks. The absorbent-side battery limits extend from receipt of the lime to sludge discharge to the final sludge disposal site.

The Data Book is intended to help engineers udnerstand the process design features, the applicable control systems, and the characteristics of equipment that are unique to lime FGD systems. It is intended to supplement, not replace, basic information on engineering design.

Additionally a section has been included to assist a utility engineer in the preparation of bid requests for an FGD system and subsequently to evaluate bids received.

1.3 DESCRIPTION OF CONTENTS

The Lime FGD Systems Data Book is organized into five major sections as discussed below:

1. Introduction

   This section describes the general background, purpose, scope, and organization of the manual.

2. Process Design

   This section identifies the chemical process design information associated with lime scrubbing systems and how the various design parameters are interrelated. In this section, emphasis is placed on understanding the method of and need for calculating material balances for lime scrubbing systems as an aid to specify and/or check process flow sheets for scrubber systems.

3. Control Systems

   This section identifies the critical parameters required to design a scrubber control system and details the field experience related to the control and operation of full scale scrubbers. Information contained in this section will aid the utility design engineer in specifying scrubber control systems that will provide economical, safe, and stable operation of the flue gas scrubbing process.

4. Equipment Design

   In this section, characteristics of specific scrubber equipment as well as design considerations and operating histories are presented. Existing lime-based FGD systems are described along with operating experience, maintenance practices, and corrective actions. This information should help specify the individual equipment items required in lime scrubbing systems.

5. Bid Preparation/Evaluation

   This section provides guidance for the specification and evaluation of lime scrubber system bids. This guidance is intended to ensure that each bid received from vendors for evaluation contains equipment of the proper size and type, meaningful guarantees to meet emission regulations under varying operating conditions, a defined maintenance schedule, and a specified degree of redundancy.

Additionally a key word glossary of lime scrubbing terms has been included at the end of the Data Book.

Numerous EPA publications and EPRI published reports provided inputs to the construction of this manual. Extensive references follow each section.

SECTION 2

PROCESS DESIGN

2.1 INTRODUCTION

This chapter of the Lime FGD Systems Data Book presents discussion of many of the major factors that affect the design of an FGD system.

All of these sections point toward the overall design of an FGD system and enumerate a number of items that must be considered in any such design.

In Section 2.2, the effects of 19 design parameters on FGD system design and their interrelation are discussed. Among these are items such as coal properties, absorber type, the effect of regulatory constraints, and redundancy.

In Section 2.3, a detailed procedure for calculating a material balance for a specific plant site is given. The step-by-step calculations and descriptions will enable a lime scrubber system design engineer to calculate a material balance for a specific plant. At the end of this section information on operable lime FGD systems is presented that can be used for comparison.

In Section 2.4, a review of the present status of FGD sludge handling and disposal is presented. For more in-depth information, the reader is referred to EPRI reports FP 671, Volumes 1 through 4.

CONTENTS

2.2 EFFECTS OF DESIGN PARAMETERS

Page

2.2.1 Coal Properties 2.2-1

    2.2.1.1 Sulfur Content and Type 2.2-1
    2.2.1.2 Ash Content 2.2-9
    2.2.1.3 Fly Ash 2.2-9
    2.2.1.4 Chloride Content 2.2-11
    2.2.1.5 Heating Value 2.2-14
    2.2.1.6 Moisture Content 2.2-14
    2.2.1.7 Combustion Variability 2.2-15

2.2.2 Boiler Characteristics 2.2-15

    2.2.2.1 Type of Boiler 2.2-15
    2.2.2.2 Size of Boiler 2.2-21
    2.2.2.3 Age of Boiler/Air Leakage 2.2-21
    2.2.2.4 Flue Gas Flow 2.2-21
    2.2.2.5 Additional Control Equipment 2.2-21
    2.2.2.6 Loading Characteristics 2.2-22

2.2.3 Flue Gas 2.2-22

    2.2.3.1 Temperature 2.2-22
    2.2.3.2 Flow 2.2-23
    2.2.3.3 Dew Point 2.2-23
    2.2.3.4 Particulate Loading 2.2-23
    2.2.3.5 Particulate Alkalinity 2.2-24

2.2.4 Lime Properties 2.2-24

    2.2.4.1 Calcium and Magnesium Contents 2.2-24
    2.2.4.2 Impurities/Grits 2.2-25
    2.2.4.3 Reactivity 2.2-26
    2.2.4.4 Size 2.2-28

2.2.5 Makeup Water 2.2-29

    2.2.5.1 Chemical Composition and Variability 2.2-29
    2.2.5.2 Source 2.2-30

CONTENTS (continued)

Page

2.2.6 Site Conditions 2.2-31

2.2.6.1 Land Availability 2.2-31
2.2.6.2 Soil Permeability 2.2-31
2.2.6.3 Ambient Humidity 2.2-32
2.2.6.4 Rainfall 2.2-32
2.2.6.5 Climate 2.2-32

2.2.7 Regulations 2.2-33

2.2.7.1 SO_2 Emission Standards 2.2-33
2.2.7.2 Particulate Standards 2.2-33
2.2.7.3 Plume Visibility Standards 2.2-33
2.2.7.4 Water and Land Requirements 2.2-34

2.2.8 Absorber Type 2.2-35

2.2.9 Waste Slurry Disposal 2.2-37

2.2.10 Redundancy 2.2-38

2.2.11 Method of Reheat 2.2-39

2.2.12 Degree of Instrumentation 2.2-41

2.2.13 Mist Eliminator Configuration 2.2-41

2.2.14 Losses Throughout the System 2.2-43

2.2.15 Process Layout 2.2-44

2.2.16 Materials of Construction 2.2-44

2.2.17 Chemistry 2.2-45

2.2.17.1 pH Gradient 2.2-45
2.2.17.2 Sulfite to Sulfate Oxidation 2.2-46
2.2.17.3 Chloride Balance 2.2-46
2.2.17.4 Liquid-to-gas Ratio 2.2-46
2.2.17.5 Point of Fresh Slurry Addition 2.2-47
2.2.17.6 Scaling 2.2-47
2.2.17.7 Oxidation of SO_2 to SO_3 2.2-49
2.2.17.8 NO_x Interferences 2.2-50
2.2.17.9 Stoichiometric Ratio 2.2-50
2.2.17.10 Lime Utilization 2.2-50

2.2.18 Process Approximations and Design Data 2.2-50

References 2.2-53

2.2 EFFECTS OF DESIGN PARAMETERS ON PROCESS DESIGN

This section discusses the major factors both inside and outside the battery limits of the SO_2 absorber that influence the design of the FGD system. These factors are listed in Tables 2.2-1 and 2.2-2.

This section summarizes information presented in the body of this data book, providing a synopsis of items that may greatly affect FGD system operation. Individual sections containing additional information are noted.

2.2.1 Coal Properties[1]

Properties of the coal fired in a utility boiler determine whether, or to what degree, particulate and SO_2 controls are needed. Typical analyses of representative U.S. coals are presented in Table 2.2-3. The power generation industry uses coal from fields throughout the country. In general, the eastern fields contain anthracite and bituminous coals of medium and high volatility while the western fields contain subbituminous and lignitic coals.

In designing an FGD system, the user has two principal means of evaluating the coal to be burned. First, he may obtain detailed laboratory analyses of the chemical and physical properties of the coal and call upon combustion experts for evaluation on the basis of experience with a similar fuel in a comparable combustion unit. If this type of information is lacking or if laboratory test results indicate marginal performance, the utility may undertake full-scale testing by burning a sample load.

Full-scale testing over a minimum 1-week period, in conjunction with use of laboratory data to predict combustion performance, is the best available means of evaluating new coal sources for a combustion unit. The short-term full-scale test, however, may not disclose all combustion problems, since some ash deposition problems occur only after a "conditioning" period (up to a few months).

2.2.1.1 Sulfur Content and Type[2]--

To meet the SO_2 emission constraints on utility boilers, personnel at some coal firing installations have considered burning low-sulfur coals. Following are some of the points to be considered.

1. Anthracite is commonly low in sulfur, but this low-volatility fuel is difficult to pulverize and burn and is not suitable for a steam generator arranged to burn high-sulfur, bituminous coal of medium to high volatility.

Table 2.2-1. FACTORS THAT INFLUENCE SCRUBBER SYSTEM DESIGN OUTSIDE THE BATTERY LIMITS

- Coal properties
    - Sulfur content, type
    - Ash content
    - Fly ash composition, particle size
    - Chloride content
    - Heating value
    - Moisture content
    - Composition variability
- Boiler design
    - Type of boiler
    - Size of boiler
    - Age of boiler
    - Flue gas flow
    - Additional control equipment
    - Loading characteristics
- Lime properites
    - Percent inert
    - Ca, Mg contents
    - Reactivity
    - Size
- Site conditions
    - Land availability
    - Soil permeability
    - Ambient humidity
    - Rainfall
    - Climate
- Regulations
    - SO_2 emission/ambient standards
    - Particulate standards
    - Plume visibility standards
    - Water/land standards
- Makeup water
    - Chemical composition
    - Source
- Flue gas
    - Temperature
    - Flow
    - Dew point
    - Particulate loading
    - Particulate alkalinity

Table 2.2-2. FACTORS THAT INFLUENCE SCRUBBER SYSTEM DESIGN INSIDE THE BATTERY LIMITS

- Absorber type
- Waste slurry disposal scheme
- Redundancy
- Reheat amount/type
- Degree of instrumentation
- Mist eliminator configuration
- Lime slaking completeness
- Fugitive losses throughout
- Process layout
- Materials of construction
- Makeup water distribution
- Chemistry
    - pH gradient throughout
    - Sulfite to sulfate oxidation
    - Chloride balance
    - Liquid-to-gas ratio (L/G)
    - Point of fresh slurry addition
    - Scaling
    - Corrosion
    - Oxidation of SO_2 to SO_3
    - NO_x interference
    - Stoichiometry
    - Lime utilization

Table 2.2-3. TYPICAL ANALYSIS OF REPRESENTATIVE U.S COALS AS RECEIVED[3]
(values in-percent except as noted)

State and county	Mining district or seam	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Heating value, Btu/lb
ALA., Jefferson	Mary Lee	2.55	28.10	58.40	10.95	1.00	13,300
Walker	Mary Lee	3.35	30.80	52.80	13.05	0.70	12,360
ARK., Franklin	Denning	2.25	14.25	74.00	9.50	1.90	14,000
COLO., El Paso	Colo. Springs	22.30	33.30	38.25	6.15	0.40	8,625
Las Animas	Trinidad	2.30	29.80	58.70	9.20	0.50	13,780
ILL., Franklin	Franklin	9.99	32.82	49.27	7.92	1.03	11,857
Williamson	Williamson	8.77	32.64	51.41	7.18	1.10	12,177
Sangamon	Springfield	13.09	36.51	41.14	9.26	3.77	10,935
St. Clair	Belleville-Saunton	11.17	39.31	39.20	10.32	4.22	11,223
Peoria	Peoria	15.41	34.34	38.52	11.73	2.97	10,422
Fulton	Fulton	16.33	35.50	37.01	11.16	2.89	10,220
IND., Clay, Greene, Vigo	No. 3	11.50	38.25	40.45	9.80	4.55	11,550
Greene, Sullivan	No. 4	13.55	33.55	45.40	7.50	0.94	11,740
Greene, Sullivan, Gibson	No. 5	11.15	35.70	42.65	10.50	4.18	11,370
Greene, Sullivan, Knox	No. 6	14.90	31.65	46.15	7.30	2.20	11,325
IOWA, Appanoose, Wayne	Mystic	7.25	36.00	47.50	9.25	3.75	11,500
Marion		6.50	39.00	46.75	7.75	5.00	10,200
Monroe		5.25	41.00	46.25	7.50	5.25	11,750
Polk		10.30	38.25	39.65	11.80	5.00	10,500
Boone		12.30	38.20	43.80	5.70	4.75	10,500
KAN., Cherokee	Cherokee	5.00	33.10	52.90	9.00	4.65	12,930
Leavenworth	Leavenworth	11.50	35.35	39.95	13.20	4.20	10,900
E. KY., Floyd, Letcher, Pike	Elkhorn	3.40	36.75	55.85	4.00	0.75	14,000
Perry, Breathitt, Knott, Letcher	Hazard No. 4	3.75	36.75	55.30	4.20	0.70	13,755
Harlan	Harlan	3.25	36.90	55.95	3.90	0.85	13,960

(continued)

Table 2.2-3. (continued).

State and county	Mining district or seam	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Heating value, Btu/lb
W. KY., Union, Webster, Hopkins, Muhlenburg	Eastern Interior Seam No. 9	4.85	36.65	49.50	9.00	3.30	12,490
MD., Allegany	Georges Creek	2.60	19.10	71.35	6.95	1.20	14,135
MICH., Saginaw	Saginaw	9.00	34.00	53.20	3.80	1.05	12,750
MO., Adair	Bevier	11.75	34.50	40.70	13.05	4.80	11,150
MONT., Carbon	Red Lodge	11.40	35.30	42.80	10.50	1.70	9,900
Carbon	Bear Creek	9.40	35.60	45.60	9.40	2.40	10,700
N. MEX, McKinley	San Juan	11.50	39.10	42.60	6.80	0.70	11,300
Santa Fe	Cerillos	3.70	35.00	49.50	11.80	1.00	12,800
N.D. Most Middle and Western Counties	(General)	36.00	29.00	28.00	7.00	0.65	6,600
OHIO, Morgan, Noble, Washington, Harrison	Mergs Creek	4.00	36.00	48.50	11.50	4.25	12,250
Belmont	Pittsburgh No. 8	5.95	37.80	46.80	9.45	4.20	12,055
OKLA., Pittsburgh	McAlester	2.00	37.25	56.25	4.50	0.75	13,500
PENN., Luzerne & Lackawanna	Northern Coal Field	3.00	6.10	82.00	8.90	0.70	13,000
Dauphin, Schuylkill, Carbon	Southern Coal Field	4.00	6.40	80.50	9.10	0.90	12,800
Cambria	Upper Killaning	2.55	16.25	71.90	9.30	2.10	13,865
	Lower Killaning	2.30	18.65	72.45	6.60	1.44	14,400
Cambria	Upper Freeport	2.75	21.60	67.40	8.25	1.45	13,930
	Lower Freeport	2.85	22.40	67.05	7.70	1.65	13,960

(continued)

Table 2.2-3. (continued).

State and county	Mining district or seam	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Heating value, Btu/lb
Clearfield	Lower Kittaning	2.70	21.15	67.85	8.30	1.85	13,940
	Lower Freeport	3.05	24.80	65.20	6.95	1.60	14,025
Somerset	Upper Kittaning	2.75	17.35	71.00	8.90	1.40	13,810
	Lower Kittaning	2.75	16.25	73.00	8.00	1.70	13,990
Westmoreland	Redstone	2.10	33.25	53.55	11.10	2.45	13,140
Allegheny	Upper Freeport	2.50	34.00	54.50	9.00	2.25	13,400
TENN., Campbell	Jellico	3.50	36.30	52.90	7.30	1.60	13,630
Bledsoe	Swanee	3.20	29.30	59.70	7.80	0.85	13,500
TEXAS, Bowie S.W. to La Salle	Lignite Fields	33.40	40.40	17.20	9.00	1.10	7,600
UTAH, Carbon	Castlegate	5.50	39.20	47.80	7.50	0.60	12,500
Summit	Wasatch	14.00	38.00	43.00	5.00	1.40	10,700
VA., Tazewell	Pocahontas	2.90	21.20	71.50	4.40	0.55	14,550
Wise	Norton	1.40	34.13	58.47	6.00	0.82	14,250
WASH., Kittitas	Clealum (Cle Elum)	8.00	34.60	44.70	12.70	0.45	11,410
Kittitas	Roslyn	3.70	34.30	48.60	13.40	0.30	12,250
Pierce	High Vol. Carbonado	3.80	36.00	51.20	9.00	0.50	13,400
Pierce	Med. Vol. Carbonado	3.80	29.30	49.90	17.00	0.50	11,500
W. VA., Monongalia, Marion, Harrison	Fairmont	1.80	37.55	54.15	6.50	2.20	13,850
Fayette	New River	2.10	22.50	72.20	3.20	0.65	14,860
Mercer	Pocahontas	2.60	17.75	75.00	4.65	0.65	14,635
Kanawha, Fayette	Kanawha	1.80	35.80	55.70	6.70	0.90	13,500
Mingo	Thacker	2.45	35.80	56.40	5.35	0.95	14,100

2. Almost all western subbituminous and lignitic coals have sulfur contents of less than 2 percent, and in most the sulfur content is under 1 percent. These western coals are easy to burn, with medium to high volatility; in this respect they are similar to the eastern and midwestern bituminous coals. Many western coals, however, have other characteristics that are markedly different from those of eastern fuels and cause significant changes in operation. While there is no typical western coal analysis, some of the major features include the following:

   - Total moisture content often ranges from 25 to over 30 percent.

   - Heating value is typically low, ranging from 6000 to 10,000 Btu/lb as received.

   - Ash content seldom exceeds 12 percent and usually ranges from 5 to 8 percent. Sodium oxide in the ash ranges from 0.5 to 8 percent or more. Potassium and iron content in the ash are frequently low, but calcium oxide content can exceed 25 percent.

   - Grindability is moderate, ranging from 40 to 70 Hardgrave Grindability Units.

3. The quantity of fuel required to sustain a given output varies with heating value. Use of western fuels generally requires more coal and may require additional capability in the pulverizer and primary air system.

4. Efficiency varies with moisture content and heating value of the fuel and with the gas volume produced by combustion. Use of western coal generally reduces furnace/boiler efficiency.

5. Coals with higher moisture content and lower heating value produce higher mass flow rates of flue gas, leading to increased gas velocity and draft loss in the convection passes. Requirements for fan power and capacity are also higher.

6. Adjustment of the air heater may be required because of moisture in the fuel. Primary air temperature may be too low for coals with higher moisture content. In addition, adjustment of the tempering air system may be required for proper control of fuel systems with variable moisture content.

7. Additional facilities for handling and storage of fuel and ash may be needed if tonnages are significantly different from those now being used and generated.

All coals used as fuel in utility boilers contain sulfur in amounts ranging from 0.5 percent to more than 5 percent. Depending on the heating value (Btu/lb) of the coal, this sulfur content may produce SO_2 in amounts ranging from 700 to 3500 parts per million (ppm) or from 0.8 to 8.5 lb $SO_2/10^6$ Btu heat input. The current Federal New Source Performance Standards (NSPS) allow a maximum of 1.2 lb $SO_2/10^6$ Btu of heat input. Proposed changes in the NSPS may call for 85 percent SO_2 removal with a maximum allowable emission of 1.2 lb $SO_2/10^6$ Btu of heat input and a maximum uncontrolled emission level of 0.2 lb $SO_2/10^6$ Btu of heat input (i.e., boilers emitting more than the amount would need FGD equipment).

To estimate the SO_2 emission (lb $SO_2/10^6$ Btu), the following equation may be used:

$(2 \times 10^4) \times$ (coal wt.% sulfur) $\times$ (fractional conversion of sulfur in coal to SO_2)/(heating value in Btu/lb).

EXAMPLE: $(2 \times 10^4) \times (3.5\%) \times$ (0.92 conversion)/(11,000 Btu/lb) = 5.85 lb $SO_2/10^6$ Btu.

If the conversion of sulfur to sulfur dioxide is unknown, use a 0.95 conversion factor for rough estimation.

Sulfur is normally present in the coal in three forms: organic sulfur compounds, pyrites (primarily FeS_2), and inorganic sulfates. All the organic sulfur is liberated when the coal is burned, but not all the inorganic and pyritic sulfur is liberated. Some of it is removed as bottom ash or is included in the fly ash. The inorganic sulfates may remain in the sulfate form; or the sulfates may be thermally decomposed to SO_2 and oxygen. The main factors that affect the action of sulfates are the type of sulfate (and hence its tendency to decompose) and the effective temperature to which the sulfate is exposed within the coal particle.

The coal must be tested to determine roughly what percentage of the organic and inorganic sulfur is converted to sulfur oxides, primarily SO_2.

Typically 95 percent or more of sulfur in coal is converted to SO_2; about 0.5 to 1.0 percent may be converted to sulfur trioxide (SO_3), which reacts with water to form sulfuric acid (H_2SO_4). If the flue gas is saturated with water and is then cooled, H_2SO_4 tends to form a mist that is difficult to remove.

In the material balance, it is assumed that all the sulfur is oxidized to SO_2. The amount of SO_2 liberated, in excess of the emission regulation, must be reacted with lime slurry. Assuming a 10 percent excess of lime in the absorbing slurry (1.1 stoichiometric ratio), 0.96 lb of lime (calcium oxide) is needed to react with each pound of SO_2.

2.2.1.2 Ash Content[4,5]--

Ash content of coal ranges from less than 4 to more than 17 percent. Some of the ash leaves the boiler with the flue gas as fly ash, and some remains in the boiler and is removed as bottom ash.

To determine the percentage of the ash that evolves as fly ash one must test the coal. The amount that is converted to fly ash is typically about 75 percent, although this may vary greatly with particular coals and with the type of boiler in which the coal is fired. In cyclone-fired boilers, about 70 percent of the ash is removed as bottom ash and 30 percent as fly ash; in pulverized-coal-fired boilers, the proportions of bottom ash and fly ash are reversed.

What is commonly termed coal ash has it origin in coal as mineral matter that includes complex metal and organic silicates, chlorides, carbonates, sulfides, sulfates, and phosphates. The principal elemental constituents are calcium, aluminum, iron, silica, magnesium, sulfur, sodium, potassium, and manganese. Most of the naturally occurring elements of the periodic table also are present as minor and trace elements.

When coal is burned, the flame temperature generally exceeds 1650°C (3000°F); however, the expanding hot gas is rapidly cooled by heat losses to the water walls and convection passes of the boiler system. During combustion and subsequent cooling, the mineral content of the coal is thermally decomposed, forming fly ash, vapor, and slag. Fly ash is the gas-borne material that flows through the boiler convection passes as discrete particles. Vaporized mineral matter usually includes sodium and potassium compounds, which can deposit on boiler tubes in the lower temperature zones of the boiler system. Slag consists of ash that is removed from wet-bottom or cyclone furnaces in a molten state.

2.2.1.3 Fly Ash[5,7,8,9]--

Fly ash has four major impacts on FGD system design:

1. It can erode the piping and pumps.

2. It can contribute to scaling or plugging within the SO_2 absorber and wet particulate scrubber, if one is used.

3. If the fly ash has alkalinity value from its available calcium oxide (CaO), sodium oxide (Na_2O), and magnesium oxide (MgO) constituents, it may reduce the requirements for lime makeup and fresh or recycled water and thus reduce cost.

4. The chemically reactive part of the solids consists of calcium sulfite and unreacted lime. When fly ash is present in the slurry, it dilutes the reactive solids, and a hold tank of larger volume may be required.

Before addressing each of these impacts, we consider briefly the effect of the fly ash on particulate removal because this largely determines the impact of particulates on the FGD system.

The fly ash carried in a flue gas stream can be removed by an electrostatic precipitator (ESP), a fabric filter (baghouse), and/or a wet scrubber. The choice of removal system is determined by the physical characteristics of the fly ash (especially resistivity and particle size), the projected operating and maintenance costs, and space or land constraints. Both ESP's and baghouses can remove over 99 percent of the particulate matter; venturi scrubbers can also remove over 99 percent if the pressure drop is high enough.[7]

High fly ash resistivity limits the power input to an ESP and hence the driving force for particle capture. Fly ash resistivity is mainly a function of the sulfur content of the coal, the gas temperature, and the chemical composition of the fly ash. Precipitator manufacturers and others have developed several indices to aid in design of precipitators for low-sulfur coal applications, which generally produce fly ashes with high resistivities.[9]

As an example of the impact of sulfur content on an ESP, a precipitator operating at about 98 percent efficiency on a coal with 2.5 percent sulfur can easily drop to below 90 percent efficiency at 1 percent sulfur. The extent of efficiency degradation is highly variable, depending largely on the plate area of the installed precipitator and the plate rapping efficiency. Performance degradation may be overcome by conditioning the flue gas, operating at higher or lower temperatures, derating the boiler, or installing more plate area.

Alternatively, operators sometimes remove both the particulates and the SO_2 in the FGD absorber. In such cases, the presence of ash particulates requires a greater purge from the absorber recirculation loop to maintain the total solids level. This in turn reduces the concentration of calcium compounds in total solids because the amount of calcium solids purged remains constant. The fly ash concentration may accentuate scaling tendencies.

As mentioned earlier, particulates that are not removed prior to the wet scrubber or absorber can cause erosion, scaling, and plugging and can reduce the demand for alkaline absorbent. Although erosion affects parts of the recirculating slurry loop, scaling and plugging are usually accentuated in areas of low flow.

Some types of fly ash offer a beneficial effect because of their alkaline constituents. A typical chemical analysis of fly ash from bituminous coal is as follows:

SiO_2	48%	MgO	0.95%
Al_2O_3	21%	TiO_2	1.32%
Fe_2O_3	18%	Na_2O	0.60%
CaO	4%	K_2O	1.40%

Some fly ashes, especially from lignite, contain high percentages of CaO, MgO, and Na_2O, and thus reduce the alkaline absorbent demand. The economic impact of these alkaline fly ashes can be significant; a "typical" ash may have less than 6 percent CaO, MgO, and Na_2O total alkalinity, whereas lignite ash may contain more than 27 percent CaO, MgO, and Na_2O total alkalinity. Examples of ash contituents are given in Tables 2.2-4 and 2.2-5.

2.2.1.4 Chloride Content--

The chloride content of coal is variable. As the coal is burned, the chlorides are volatilized and carried out with the flue gas stream. Experience has proved the need for considering the corrosive properties of chlorides when selecting construction materials for scrubbers and absorbers. The use of 316L stainless steel has sometimes been successful, but because the 300 series stainless steels are prone to chloride stress corrosion cracking, they should be used in such environments only with caution.[10]

The chloride level in the recirculating SO_2 absorbent slurry is controlled by the chloride content of the coal fired, the allowable level of chlorides in discharges from the sludge

Table 2.2-4. AVERAGE ASH CONSTITUENTS OF THREE RANKS OF COAL[6]

Bituminous states (average percent of ash constituents)

State	Ash	S	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	Mgo	Na_2O	K_2O	SO_3	Def. temp., °F	Soften temp., °F	Fluid temp., °F
Alabama	9.0	1.6	43.7	26.4	19.9	1.18	0.23	2.98	1.29	0.27	2.36	2.13	2385	2318	2490
Arkansas	8.25	2.5	24.8	19.75	23.4	0.95	1.06	13.1	4.9	1.45	1.25	10.15	2175	2270	2400
Illinois	10.05	3.35	45.5	19.1	23.33	0.95	0.157	5.16	0.89	0.373	1.62	1.73	2016	2085	2290
Indiana	8.62	2.88	46.9	22.78	20.7	1.08	0.145	3.39	0.88	0.45	2.43	1.07	2214	2325	2512
Iowa	13.4	5.15	34.3	13.95	33.4	0.85	0.29	9.65	1.25	0.5	1.2	3.05	1975	2025	2165
Kansas	10.45	4.0	38.2	16.35	37.75	0.65	0.16	6.75	0.55	0.3	1.0	2.7	1970	2025	2200
E. Kentucky	6.32	1.07	46.2	27.5	10.5	1.43	0.13	2.16	1.04	0.45	1.86	2.17	2463	2615	2710
W. Kentucky	10.14	3.03	47.86	23.05	21.76	1.20	0.16	2.19	0.92	0.25	2.37	1.00	2034	2352	2501
Maryland	9.5	1.3	51.65	30.35	10.05	1.4	0.21	1.85	0.65	0.6	2.55	0.85	2705	2790	2740
Missouri	11.73	4.6	42.2	15.8	31.05	0.7	0.1	4.9	0.65	0.15	2.1	2.45	1978	2028	2295
Ohio	11.6	3.6	31.6	22.9	28.0	1.0	0.21	2.0	0.69	0.24	1.5	1.14	2092	2206	2411
Pennsylvania	10.23	1.95	45.43	27.55	21.15	1.05	0.27	1.85	0.55	0.21	1.95	1.26	2377	2456	2579
Tennessee	10.4	2.0	47.7	36.32	15.9	1.19	1.86	1.91	1.25	0.31	2.68	1.6	2411	2456	2610
Utah	7.7	0.76	51.4	15.1	7.4	0.96	0.58	11.8	3.3	1.7	0.6	6.0	2166	2250	2409
Virginia	7.8	1.09	45.6	27.8	14.6	1.34	0.24	4.5	1.5	0.88	2.1	2.5	2377	2485	2623
N.W. Virginia	10.21	2.56	41.20	26.11	23.38	1.16	0.40	3.39	0.85	0.40	1.62	2.36	2331	2376	2529
S.W. Virginia	7.73	1.00	50.86	30.89	10.50	1.52	0.27	2.07	0.81	0.56	1.74	1.67	2682	2638	2737

Subbituminous states (average percent of ash constituents)

State	Ash	S	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	MgO	Na_2O	K_2O	SO_3	Def. temp., °F	Soften temp., °F	Fluid temp., °F
Montana	12.6	0.59	35.4	21.5	5.31	0.83	0.41	13.46	4.63	2.8	0.67	13.33	2355	2435	2505
New Mexico	10.53	1.13	49.2	21.82	13.76	1.05	0.06	6.38	2.0	0.67	0.58	4.68	2318	2372	2474
Wyoming	10.4	1.2	31.6	16.9	9.7	1.4	0.36	20.1	4.6	0.15	0.55	15.3	2450	2510	2630

Lignite state (average percent of ash constituents)

State	Ash	S	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	MgO	Na_2O	K_2O	SO_3	Def. temp., °F	Soften temp., °F	Fluid temp., °F
North Dakota	11.8	0.98	26.3	12.1	6.85	0.73	0.21	21.1	6.4	4.42	0.33	20.6	2180	2237	2303

Table 2.2-5. ASH ANALYSES OF SELECTED COALS[6]

	Type of coal		
	Lignite	Subbituminous	Bituminous
Coal analysis			
Btu/lb	6500	9086	10,290
Ash, %	10	10.6	18
Moisture, %	40	27.2	10.4
Sulfur, %	0.8	1.0	5.1
Ash analysis, %			
SiO_2	28.4	34.2	44.6
Al_2O_3	11	15	18
TiO_2	0.4	0.8	0.6
Fe_2O_3	14	12	18
CaO	18	18	5
MgO	5	4.5	1.2
Na_2O	7.0	0.3	1.35
K_2O	0.7	0.3	1.9
SO_3	19.8	17	5.0
Fouling potential	High	Medium	High
Slagging potential	Severe	High	Severe

pond to adjacent bodies of water, and the use of cooling tower blowdown. The intent of current water pollution legislation is to enforce "zero discharge" from point sources; this means that the utility FGD systems must operate in a "closed-loop" mode. The result of closed-loop operation is that aqueous slurries with very high chloride levels (5,000 to 10,000 ppm) could be recirculated.[11] Saturation is not reached because of chloride loss in the interstitial water in the calcium sulfate/sulfite sludge.

In some FGD systems in Japan, the clear liquor purge rate is controlled by the chloride content of the slurry, which may necessitate excessive blowdown.

Although the effect of chlorides is the subject of ongoing research, the design engineer must be aware of possible difficulties caused by the chloride content of the coal, the impact of "closed-loop" operation, and the chloride in cooling tower blowdown.

2.2.1.5 Heating Value--

The heating value of various coals ranges from under 9000 Btu/lb to over 12,000 Btu/lb. Accordingly, to obtain a million Btu of heat input in a boiler, the feed rate of coal may range from under 83 lb of coal with high heat content to over 111 lb of coal with low heat content. With the increased coal feed rate, the resulting greater quantities of fly ash may call for additional particulate collection capacity (retrofit), necessitating additional capital expenditures and higher operating and maintenance costs.

Use of coal with lower heat content also requires greater capacity for coal handling, processing, and grinding if it replaces a higher-heat-content coal for which the unit was designed. Again, the capital, operating, and maintenance costs rise.

2.2.1.6 Moisture Content--

In general, coals with a higher moisture content reduce pulverizer capacity. An increase in moisture content also entails the need for much warmer air and for more air to dry and carry the fuel to the burners. Both surface and inherent moisture are present in coal. Surface moisture is affected by weather and by the methods of mining, fuel preparation, and transportation (slurry pipelines); typical surface moisture is 8 to 10 percent of dry weight, with variations. Surface moisture is independent of the type of coal. Inherent moisture is that which is intimately associated with the coal in the particle structure. Western coals, especially lignite and subbituminous coal, are high in inherent moisture.

Most utility and industrial combustion systems can handle wet coal (up to 20% moisture content) on an intermittent basis. Units designed to burn lignite and subbituminous coal must handle total moisture contents as high as 40 percent. Significant changes in moisture content will require modifications of the air preheater system to provide higher air temperatures in the pulverizer. Modifications of fuel drying systems are possible, but generally costly.

Since higher coal moisture contents necessitate the use of more coal for the same net heat input, more air is required for proper combustion. The greater air volume calls for larger SO_2 absorbers and/or more absorbers to accommodate the additional flue gas volume. Additionally, the greater the air volume, the greater the makeup requirement for water. More water is absorbed as the air is adiabatically cooled in either the wet particulate scrubber or the SO_2 absorber, even though the coal supplies additional moisture. The increased water needed for adiabatic cooling may be a major concern if freshwater supplies are limited.

2.2.1.7 Combustion Variability--

As vegetable matter is transformed in stages from wood to peat, lignite, subbituminous coal, bituminous coal, and anthracite, its moisture content drops from 60 percent to 5 percent; volatile matter decreases from 70 to less than 10 percent; and fixed carbon increases from 20 to about 80 percent. Tables 2.2-6, 2.2-7, and 2.2-8 show some of the chemical and physical properties of various coals.

The FGD system designer should be concerned with the variability of the sulfur, moisture, chloride, and heat contents of the individual coals within a seam or from seam to seam. Table 2.2-9 shows the variability in sulfur content as sampled from unit train coal deliveries. Note that the sulfur content can vary by 50 percent from the long-term average if a single 3-h sampling time is used to evaluate coal sulfur content. Therefore, the designer should be aware not only of "average" values, but also of the variability of these values over the averaging time required by the applicable regulations.

2.2.2 Boiler Characteristics

2.2.2.1 Type of Boiler--

Three general types of coal combustion systems are used by industries and utilities in this country: stokers, pulverized-coal-fired units, and cyclone-fired units.

Table 2.2-6. CONSTITUENTS AND PROPERTIES OF SELECTED COALS[6]

State	Analysis of Coals, as received						Coal type
	H_2O	VM[a]	FC[b]	Ash	Sulfur	Btu	
Pa.	2.0	1.8	86.2	10	0.79	13070	Anthracite
Pa.	4.0	17	69	10	1.63	13430	Bituminous
Pa.	3.0	23.1	63.9	10	2.17	13600	Bituminous
Ky.	3.0	34.4	56.6	6.0	0.72	13800	Bituminous
Ohio	6.0	34.8	49.2	10	2.44	12450	Bituminous
Ill.	14	34.3	39.7	12	4.07	10470	Bituminous
Iowa	13.9	36.9	35.2	14	6.15	10244	Subbituminous
Colo.	24	30.2	40.8	5	0.36	9200	Subbituminous
Wyo.	24	30	36	10	0.33	8450	Subbituminous
N. Dak.	40	27.6	23.4	9.0	1.42	6330	Lignite

[a] Volatile material.

[b] Fixed carbon.

Table 2.2-7. COMPOSITION OF VARIOUS GRADES OF U.S. COALS[3]
(percent)

Fuel classification		Moisture (as-received)	Volatile matter	Fixed Carbon	Ash	Sulfur	Hydrogen	Carbon	Nitrogen	Oxygen
Wood		46.9	78.1	20.4	1.5		6.0	51.4	0.1	41.0
Peat	Minnesota	64.3	67.3	22.7	10.0	0.4	5.3	52.2	1.8	30.3
Lignite	N. Dakota	36.0	49.8	38.1	12.1	1.8	4.0	64.7	1.9	15.5
Lignite	Texas	33.7	44.1	44.9	11.0	0.8	4.6	64.1	1.2	18.3
Subbituminous C	Wyoming	22.3	40.4	44.7	14.9	3.4	4.1	61.7	1.3	14.6
Subbituminous B	Wyoming	15.3	39.7	53.6	6.7	2.7	5.2	67.3	1.9	16.2
Subbituminous A	Wyoming	12.8	39.0	55.2	5.8	0.4	5.2	73.1	0.9	14.6
Bituminous high volatile C	Colorado	12.0	38.9	53.9	7.2	0.6	5.0	73.1	1.5	12.6
Bituminous high volatile B	Illinois	8.6	35.4	56.2	8.4	1.8	4.8	74.6	1.5	8.9
Bituminous high volatile A	Pennsylvania	1.4	34.3	59.2	6.5	1.3	5.2	79.5	1.4	6.1
Bituminous medium volatile	W. Virginia	3.4	22.2	74.9	2.9	0.6	4.9	86.4	1.6	3.6
Bituminous volatile	W. Virginia	3.6	16.0	79.1	4.9	0.8	4.8	85.4	1.5	2.6
Semianthracite	Arkansas	5.2	11.0	74.2	14.8	2.2	3.4	76.4	0.5	2.7
Anthracite	Pennsylvania	5.4	7.4	75.9	16.7	0.8	2.6	76.8	0.8	2.3
Metaanthracite	Rhode Island	4.5	3.2	82.4	14.4	0.9	0.5	82.4	0.1	1.7

Table 2.2-8. CLASSIFICATION OF COAL BY RANK[6]

Class[a]	Group	Fixed Carbon limits, % (Dry, mineral-matter-free basis)		Volatile matter limits, % (Dry, mineral-matter-free basis)		Calorific value limits, Btu/lb (Moist,[b] mineral-matter-free basis)		Agglomerating character
		Equal to or greater than	Less than	Greater than	Equal to or less than	Equal to or greater than	Less than	
Anthracite	1. Metaanthracite	98			2			Nonagglomerating
	2. Anthracite	92	98	2	8			
	3. Semianthracite[c]	86	92	8	14			
Bituminous	1. Low volatile bituminous coal	78	86	14	22			
	2. Medium volatile bituminous coal	69	78	22	31			
	3. High volatile A bituminous coal		69	31		14,000[d]		Commonly agglomerating[e]
	4. High volatile B bituminous coal					13,000[d]	14,000	
	5. High volatile C bituminous coal					11,500 10,500[e]	13,000 11,500	Agglomerating
Subbituminous	1. Subbituminous A coal					10,500	11,500	
	2. Subbituminous B coal					9,500	10,500	
	3. Subbituminous C coal					8,300	9,500	Nonagglomerating
Lignite	1. Lignite A					6,300	8,300	
	2. Lignite B						6,300	

[a] This classification does not include a few coals, principally nonbanded varities, that have unusual physical and chemical properties and that come within the limits of fixed carbon of calorific value of the high volatile bituminous and subbituminous ranks. All of these coals either contain less than 48% dry, mineral-matter-free fixed carbon or have more than 15,500 moist, mineral-matter-free Btu/lb.

[b] Moist refers to the natural inherent moisture of the coal but not including visible water on its surface.

[c] If agglomerating, classify in low volatile group of the bituminous class.

[d] Coals having 59% or more fixed carbon on the dry, mineral-matter-free basis are classified according to fixed carbon, regardless of calorific value.

[e] There may be nonagglomerating varities in these groups of the bituminous class, and there are notable exceptions in high volatile C bituminous group.

Table 2.2-9. COAL ANALYSES AND SULFUR VARIABILITY[a] OVER VARIOUS AVERAGING TIMES[12]

Coal type	Plant size, MW	Maximum average sulfur content, %				
		Long-term	Annual	30 days	1 day	3 h
Eastern bituminous, 14% ash, 12,000 Btu/lb	25	7.00	7.36	8.27	9.36	9.73
	500	7.00	7.23	7.79	8.88	9.23
	1000	7.00	7.22	7.75	8.78	9.19
Eastern bituminous, 14% ash, 12,000 Btu/lb	25	3.50	3.68	4.13	4.68	4.86
	500	3.50	3.62	3.89	4.44	4.61
	1000	3.50	3.61	3.87	4.39	4.59
Western subbituminous 8% ash, 10,000 Btu/lb	25	0.80	0.84	0.96	1.12	1.18
	500	0.80	0.83	0.90	1.05	1.10
	1000	0.80	0.83	0.89	1.03	1.09

[a] **Distribution from unit train sampling.**

In stokers, sized coal with a minimum of fines is burned on or above a grate. Stoker designs include hand-fired units, stationary grates, vibrating grates, spreader stokers, underfeed stokers, and traveling grates. The large industrial stokers are primarily traveling-grate and spreader units.

Stoker furnaces are limited in feed rate and generally are used on units rated at less than 600 million Btu/h heat input. Free-burning bituminous coal and lignite are commonly used. Anthracite is generally unsatisfactory because it is a low-volatility fuel and does not burn easily.

Pulverized-coal-fired units operate on the principle of suspension burning. Coal is pulverized to about 200-mesh size or finer and injected into the furnace pneumatically. These furnaces are classified as dry-bottom or wet-bottom, depending on whether the ash is removed in the solid or molten state. In the modern direct-fired system, hot primary air is ducted to the pulverizer, where the raw coal is dried and pulverized. The mixture of hot air and pulverized coal is continuously conveyed to the burners. The current maximum capacity of an individual pulverized-coal burner is about 164 million Btu/h. Although a unit may have as many as 70 burners, 16 to 30 is more common.

Cyclone-fired coal combustors burn coarse coal, approximately -4 mesh, in a horizontal cylinder into which part of the combustion air is introduced tangentially to impart a whirling or centrifugal motion to the coal. Combustion temperatures are high, causing the ash to melt and adhere to the walls of the cyclone furnace. The ash is removed as slag. Less than 2 percent of the utility coal combustion systems are cyclone fired.

Various types of furnace/boiler configurations are available.

The type of boiler determines to a large extent the volume of fly ash that the downstream units receive and to some extent the volume of flue gas that the FGD systems must treat. Few utility boilers use the stoker design; pulverized-coal-fired boilers usually evolve more than twice as much fly ash from a given coal as do the cyclone-fired boilers. This difference is entirely due to boiler design characteristics and the size of the coal particles.

Depending on the type and effectiveness of the particulate removal device (ESP, baghouse, wet scrubber), FGD system designers may or may not need to be concerned about boiler type.

2.2.2.2 Size of Boiler--

As the size of the boiler (measured by its power generating capacity) increases, the volume of flue gas treated by an FGD system also increases. Boiler size largely determines the size and number of SO_2 absorber units and the size of the whole FGD system. A common conversion factor is 3000 acfm per MW of generating capacity, assuming that air leakage is not excessive.

2.2.2.3 Age of Boiler/Air Leakage--

The FGD system must be designed to handle more gas in later years. With respect to new FGD installations, the age of the boiler has only one major effect on FGD system design: as the boiler ages and leaks occur, the volume of flue gas the FGD unit must handle will increase as a result of increased excess air requirements or of increased air leakage. Estimates of the expected increase in flue gas flow should be included in the initial design, taking into consideration the design life expectancy of the FGD system and the remaining life of the boiler. Furthermore, an increase in particulate carryover usually accompanies an increase in gas volume.

2.2.2.4 Flue Gas Flow--

The primary factor in determining absorber size and cost is the flue gas flow resulting from combustion of the coal. The volatilized combustion products, NO_x, SO_x, chlorides, fly ash, etc., must be treated to remove the species that are generated in excess of the allowable levels.

FGD system designers should obtain best estimates of all the critical design parameters and consider the variability of these parameters within the averaging time specified in the emission permit. Provision for redundancy in critical units, such as the SO_2 absorber, should be viewed in light of current and projected removal requirements and the projected increase in flue gas and particulates resulting from increasing combustion air requirements and air leakage as the boiler ages.

The design objective is installation of an FGD unit that will remove the pollutants required while operating reliably, so that boiler capacity reductions are minimized over the expected life of the FGD unit.

2.2.2.5 Additional Control Equipment--

In addition to SO_2 removal, operations of utility boilers must remove particulates to the mandated emission level. ESP's, baghouses, and/or wet particulate scrubbers are used to remove a major portion of the particulate loading. Improving particulate removal, so that flue gas treated by the SO_2 absorber is as clean as possible, is often a goal of the FGD system designer. When an ESP is used for particulate removal and upgrading of existing facilities is needed, the various alternatives include conditioning the flue gas, reducing the temperature of the flue gas stream, and installing additional plate area for particulate collection.

Flue gas conditioning affects surface conductivity of the particles by the injection of sulfuric acid, sulfamic acid, sulfur trioxide, or sodium or iron salts to yield a more easily collectible fly ash.

Reduced temperature sometimes improves ESP operation. The gas temperature may be reduced by modifying the air preheater; however, "cold end" corrosion due to condensation of sulfuric/sulfurous acid might then occur in the preheater.

The most common method of upgrading precipitator performance is to install additional ESP collection plate area. This will permit adequate collection of the increased fly ash caused by changes in coal ash or sulfur content, reduced capacity of the existing ESP, or other factors.

The particulates not removed ahead of the FGD system can be removed in a properly designed scrubber. Removing particulates in the SO_2 absorber can contaminate the lime slurry; however, the particulates removed may act as a fixation aid in lime sludge disposal. At some sites, fly ash that has been removed ahead of the scrubber or the absorber is added to the sludge to aid in fixation.

2.2.2.6 Loading Characteristics--

Boiler operation has a direct effect on the mode of operation of the FGD system. If the boiler handles peak loads, then the FGD unit undergoes highly cyclical operation and the removal cost per unit SO_2 is higher than normal.

If the boiler handles base loads, the FGD unit can be expected to operate at fairly steady-state conditions, which would be ideal. Steady-state operation reduces the operating and maintenance costs and allows for optimization of operating practices.

2.2.3 Flue Gas

2.2.3.1 Temperature--

The inlet flue gas temperature determines the amount of water that evaporates when the gas is cooled in either an SO_2 absorber or a wet particulate scrubber. This has a major impact on the overall FGD system water balance. The inlet gas temperature also affects decisions on whether the scrubber or the absorber should be lined and what type of liner should be used.

Selection of liner material is based on the ability to withstand the flue gas temperature if water flow to the presaturator section is interrupted. Instrumentation may reduce the probability of damage by activating a flue gas bypass, a backup water deluge system, or a combination of both. The liner may be protected if a bypass for the flue gas can be tripped either by a temperature sensor set above the adiabatic gas temperature but below the temperature of lining damage or by a flow sensor that signals when the water supply is interrupted. As an alternative, a backup pumping system could be activated by a temperature excursion; the deluge effect might reduce the flue gas temperature enough to prevent lining damage. In a combination option, insufficient deluge (as indicated by the flue gas temperature exiting the vessel), could trigger the bypass.

2.2.3.2 Flow--

The volume of flue gas to be handled per FGD train and the desired gas velocity in the train largely determine the dimensions of the particulate scrubber, if needed, and of the SO_2 absorber. Furthermore, the availability of space can influence the design. Peaking load of the boiler also affects the number and size of FGD trains, depending on the turndown ratio of the system.

2.2.3.3 Dew Point--

After particulates and SO_2 are removed, the flue gas stream leaves the SO_2 absorber through the mist eliminator for removal of entrained liquid droplets, which contain both suspended and dissolved solids. The gas stream is saturated with water vapor. The stream passes through the ductwork at about 128°F. It may be further cooled at this stage, causing condensation on the equipment surfaces. The temperature at which condensation begins is known as the "dew point." The condensate is a dilute solution of sulfurous and sulfuric acid, which can cause major corrosion in the ducting, stack, and equipment downstream from the absorber.

Because corrosion has been widespread in FGD systems, flue gas reheat systems have been installed in many units. Reheat can be accomplished by: (1) bypassing a portion of the flue gas stream (if SO_2 emission regulations allow), (2) installing in-line, direct-fired systems or in-line, indirect steam or hot water systems, or (3) heating outside air with direct or indirect systems for mixing with the cleaned flue gas stream.[12] The subject is discussed further in Section 4.11 - Reheaters.

2.2.3.4 Particulate Loading--

The mode of firing the boiler determines the percentage of the coal's total ash content that leaves with the flue gas as fly ash. Fly ash in most FGD systems is removed by an ESP, a fabric filter, or a wet particulate scrubber. Removing particulates prior to the SO_2 absorption step reduces the solids content of the absorber recycle stream.

2.2.3.5 Particulate Alkalinity--

Some coal fly ashes are alkaline, especially lignite ash and occasionally subbituminous coal ash. A well-documented coal source yielding alkaline ash is the Colstrip seam. Refer to EPRI report entitled "Scrubbing Systems of Low Sulfur Alkaline Ash Coals." The natural alkalinity of this particular fly ash, which is approximately 20 percent CaO, reduces the amount of lime that must be added to the absorbers at the Colstrip units of Montana Power Co.[14]

By way of contrast, bituminous fly ashes normally contain less than 5 percent alkalinity as CaO. Examples are presented in Tables 2.2-4 and 2.2-5.

Since the alkalinity of the fly ash may yield definite benefits by reducing absorbent costs, the designers should investigate the properties of the fly ash and the potential effects on the FGD system.

2.2.4 Lime Properties

Properties of lime are examined in detail in Sections 4.4 and 4.5, but their effects on system design are briefly discussed here.

2.2.4.1 Calcium and Magnesium Contents--

Lime is normally a product of calcination of limestone, though some lime is produced by calcination of sea shells. It consists primarily of the oxides of calcium and magnesium. On the basis of their chemical analyses, limes may be classified into three groups:

1. High-calcium quicklime, containing less than 5 percent MgO.
2. Magnesian quicklime, containing 5 to 35 percent MgO.
3. Dolomitic quicklime, containing 35 to 40 percent MgO.

The characteristics of lime are discussed in much more detail in Section 4.4. Work on lime-based SO_2 removal at Shawnee Station of TVA and by Louisville Gas and Electric (LG&E), together with other EPA research indicates that 1000 to 4000 ppm of soluble magnesium ions (Mg^{++}) in the recirculating slurry can significantly affect the ability of a lime absorbent slurry to remove SO_2 from a flue gas stream. The magnesium ions (Mg^{++}) increase the absorption capacity of liquid slurry and can depress sulfate supersaturation.[15] In a recent test at LG&E, SO_2 removal increased from about 83 percent with calcitic lime to 95 percent by addition of 3000 ppm of Mg^{++} to the lime slurry.[15] When soluble magnesium values exceeded 5000 ppm, only slight additional SO_2 removal was observed. It should be noted that magnesium sulfite removes SO_2 at least as well as calcium sulfite ($CaSO_3$) and that magnesium sulfite and bisulfite are much more soluble in aqueous slurries than $CaSO_3$. This is important because Mg^{++} reduces the tendency for scale formation. Additional work in this area is reported by EPA, Kellogg, Dravo, and Combustion Engineering.

A disadvantage is that Mg^{++} is more likely to be carried over from the sludge pond in any aqueous discharge and may pollute local waters.

Thiosorbic^R lime has received wide attention and is discussed in Section 4.4. Dravo has patented this magnesium-promoted lime for use in increasing the SO_2 removal capabilities of FGD systems. The patent, however, is being challenged in court. Naturally occurring magnesium has been cited as the reason for reported increases in SO_2 removal in several operating lime FGD systems. In successive runs in the same SO_2 absorbers of a lime FGD system with constant liquid-to-gas (L/G) ratio and identical lime addition rates, SO_2 removal efficiencies reportedly were increased by the presence of Mg^{++} from the 72 to 88 percent range to the 94 to 99 percent range on an inlet flue gas stream of 3000 ppm of SO_2.

The benefits of Mg^{++} in promoting SO_2 removal and in reducing scaling tendencies are gaining acceptance in FGD technology and should be carefully considered in the design of a lime FGD system.

2.2.4.2 Impurities/grits--

With high-quality chemical limes that have been thoroughly calcined and have a loss-on-ignition of 1 to 1.5 percent or less as CO_2, the total grit content that must be wasted will be only 1 to 2 percent of the weight of the lime. Grit losses, however, may range up to 5 percent or more with lime of poor quality. Included in the grit, as well as the carbonate core, are insoluble silicates and lesser amounts of aluminates, sulfates, and ferrites, all of which are impurities occurring in the limestone before it was calcined. When the grit is ejected from the slaker, it resembles a mass of wet sand particles of a size ranging from 1/4 in. to 100 mesh.

Degritting is performed to improve lime quality and to reduce abrasion and wear on equipment. In extreme cases, cast-iron centrifugal pumps have been worn out within a month when pumping lime slurry that has not been degritted. With degritting, the same equipment can operate for 2 years or more.

Degritting is performed in the dilution tank adjacent to the slaking chamber. The slurry, or paste, is dispersed over a weir into the dilution chamber and diluted by water sprays as it passes. The heavier grit particles settle rapidly to the bottom and are removed automatically by rakes that drag the grit up an incline and out the chamber or to a classifier in the bottom of the dilution chamber, where the grit is washed and a small amount of slaked lime particles is recovered and mixed into the diluted slurry. The washed grit is then disposed of manually or automatically.

2.2.4.3 Reactivity--

This topic, covered in more detail in Section 4.5, Lime Slurry Preparation, is summarized briefly here. The rate of reaction of the lime when being slaked is a direct function of its size, how well it was fired, and the percentage of grit. The rate of reaction also controls the temperature of the lime slaking and/or dilution equipment. It is most desirable to complete slaking in 5 to 10 min while maintaining a slaker temperature of approximately 200°F. Temperatures are higher if the lime is more finely ground, because the higher surface area of smaller particles leads to more rapid reaction. The slaking time required for the size of lime particles selected should be considered in design of the slaker and/or hold tanks in the lime slurry preparation system.

The speed of slaking and the maximum temperature are influenced by how well the lime was calcined. The most important test in determining optimum slaking is to measure reactivity of the lime in water -- specifically, how much the temperature increases and in what length of time. In this test, a specific weight of lime of a prescribed degree of fineness is added to a specified volume of water at 77°F in a calorimeter; the temperature is measured at intermediate points and at completion of hydration. This test is standardized by the American Water Works Association (AWWA B202) and the ASTM in specification C 110 on Physical Tests of Lime.

Reactivity of the lime is classified on the basis of the time needed to produce a temperature rise of 40°C (72°F), as follows:

	No. of minutes	Time for completion
High reactivity	3 or less	10 min or less
Intermediate reactivity	3 to 6	10 to 20 min
Low reactivity	more than 6	20 min or more

Generally limes of high reactivity are soft-burned, i.e., calcined either at temperatures from 900° to 1000°C (1650° to 1850°F) or at temperatures from 1200° to 1300°C (2200° to 2400°F) for a short duration. The result is a reactive, porous lime of lower density that slakes rapidly with a high temperature rise. Limes of low reactivity are the converse, i.e., hard-burned, denser, and heavier; they slake more slowly and evolve heat more gradually, so that the temperature rise is appreciably less. Dolomitic limes are inherently of low reactivity in varying degrees, regardless of how they are calcined.

Slaking temperatures can be elevated artificially by using more vigorous agitation and hot water for slaking, or by using lime of finer particle size, such as pulverized lime. By such measures the slaking rate may be increased so that a lime of intermediate reactivity approximates the behavior of a highly reactive lime. If these methods are applied to a highly reactive lime, the slaking is extremely rapid, almost instantaneous, so that the lime and water literally explode on contact. This dangerous practice, potentially harmful to employees and equipment, also produces slaked lime of poor quality. A complete slaking time of 5 to 10 min is much more desirable. Conversely, the efficiency of a high quality, reactive lime can be seriously impaired by using too much cold water, especially with lime in lumps or large pebbles that is inadequately mixed or agitated. The resultant slurry may be coarse, fast settling, and incompletely slaked. The slaking conditions, then, can enhance the efficiency of a lime of mediocre (possibly poor) quality and can impair the efficiency of a high-quality lime.

Two extreme conditions should be avoided:[16]

1. If the excess of slaking water is too great, and particularly if the water is cold, an adverse reaction called "drowning" occurs. The surface of the quicklime particle hydrates quickly, but the mass of hydrate formed impedes penetration of the water into the center of the particle and delays rupture of the particle into microparticles. The rise in temperature is inhibited and slaking is delayed, causing coarser hydrate particles and badly delayed or incomplete hydration.

2. At the other extreme, adding insufficient water to the lime, causes the hydrate to be "burned," because temperatures are higher (250° to 500°F) than the desired level, just below boiling. Too much water is lost as steam, and unhydrated particles may remain. The heat can be so intense that paint on the equipment blisters or ignites and that dehydration of initially hydrated lime particles occurs.

The lime selected for an FGD system must be properly fired and of good quality to ensure proper slaking. If the lime is "overburned," then the surface area of the lime particles is not reactive; and any reactive lime is trapped inside this encapsulation, leading to a higher percentage of unreactive material or grits. Possible loss of available lime should be considered in design of a lime feeding system. Often systems are designed with a feeding capacity from 10 to 20 percent greater than that needed to allow for unreactive material.

The designer should know the average percentage of inerts or insolubles and the range of these values for the grade of lime selected; these variables affect the design of handling, slaking, and storage equipment and the sizing of equipment for removal and storage of inerts.

2.2.4.4 Size--

Lime is available in relatively standard sizes, as follows:

1. Lump lime - produced in vertical kilns in sizes ranging from 8 in. diameter down to 2 to 3 in.

2. Crushed or pebble lime - the most common form, produced in most kiln types, ranging from about 2 to 1/4 in.

3. Granular lime - obtained from Fluo-solids kilns in sizes ranging from 100 percent passing a No. 8 sieve to 100 percent retained on a No. 80 sieve (a dustless product).

4. Ground lime - obtained by grinding the larger-sized materials or screening off the fines; typically almost 100 percent passes a No. 8 sieve and 40 to 60 percent passes a No. 100 sieve.

5. Pulverized lime - obtained by more intense grinding than that yeilding ground lime; nearly 100 percent passes a No. 20 sieve and 85 to 95 percent passes a No. 100 sieve.

6. Pelletized lime - made by compressing lime fines into about 1-in. pellets or briquettes.

The need for these several sizes has evolved from the process requirements of various systems. The most common lime used in FGD systems is the crushed (pebble) size, which gives good, controlled rates of reaction.

2.2.5 Makeup Water

Water is lost from a scrubbing system in the form of water vapor and entrained liquid particulate in the saturated flue gas. It is also lost in disposal of sludge or gypsum byproduct. (An EPRI report, "Lime/Limestone Scrubber Operation and Control Study," gives further details.) The system uses water in slaking, in dilution of lime slurry, in the mist eliminator wash, in pump seals, and at other points.

The need for makeup water is directly proportional to such uses in the system. Chemical composition of the makeup water is important.

2.2.5.1 Chemical Composition and Variability[16]--
The quality of the water for slaking lime is more critical than for any other scrubber use. Water should be of (or near) potable quality. Waste or recycle process waters containing sulfites and sulfates retard the slaking process and reduce the quality of the resulting lime slurry. Poor slaking water causes a larger average size of the slacked particles; the resulting reduced surface area retards reactivity in a scrubber. In fact, some of the lime does not hydrate and is wasted. It appears that the lime precipitates the SO_3 and SO_4 ions as calcium sulfite/sulfate, which coats the unreacted CaO particles and prevents the complete penetration of water.[16]

Once the lime has been slaked, however, recycled or waste process water can be used to dilute the thick lime slurry to the desired consistency. The SO_3 and SO_4 ions produce little or no effect on the quality of the diluted lime slurry.

In the SO_2 absorber (or the wet particulate scrubber, if the flue gas passes through one prior to the SO_2 absorber), water evaporates and the moisture content of the flue gas is increased as the flue gas stream is cooled from about 300°F to its saturation temperature of about 128°F.

The presence of Mg^{++} or sodium ions (Na^{++}) in the SO_2 absorber makeup water is beneficial because the sulfite form of both cations is much more water-soluble than the calcium sulfite/sulfate; the greater solubility should improve the SO_2 removal and aid in reduction of scaling. The quality of water required for slaking and dilution is discussed further in Section 4.5.4.4.

The mist eliminator wash may be fresh, recycled, or waste process water, or any combination of fresh and recycled water. Although all fresh water would be ideal, closed-loop operation often requires a mix. Continuous wash is often done with recycled water, whereas high-volume, intermittent wash is done with fresh water. Since the trend in construction of mist eliminators is toward the chevron baffle unit made of plastic or other corrosion-resistant materials (e.g. Hastalloy), the chemical makeup of the water normally has little effect except for formation of scale.[17]

Freshwater is recommended for pump seals because the heat associated with pump operation could cause deposition of the sulfate and other solids from recycled pond water and consequent pump failure.

2.2.5.2 Source--

The following sources of makeup water are discussed below: freshwater, sludge pond recycle water, waste process water, cooling tower blowdown, and rainfall.

Freshwater may come from a river, a lake, a municipal water system, or other source. For pump seals and mist eliminator wash, freshwater is most desirable. Its use is limited, however, by concern for the system water balance and closed-loop operation. Normally it is used in the most critical areas where no other water is suitable, i.e., in lime slaking, in intermittent mist eliminator wash,[17] and as dilution for supernatant liquid.

Sludge pond water is decanted from the calcium sulfite/ sulfate sludge either in a settling pond or in a filtration step. This water is often a mixture of aqueous streams from all points within the FGD system. The sulfite, magnesium, and sodium ions in this water are ultimately beneficial to the SO_2 absorption process. Undesirable ions include heavy metals (because of water pollution concerns), sulfate (because it can render the absorbent unreactive or increase scaling potential), and chloride (because it can corrode materials). Sludge pond recycle water is used wherever fresh water is not required.

Waste process water streams must be evaluated in terms of availability, chemical composition, and variability of chemical composition. If these streams contain undesirable chemical constituents or if the reliability of stream supply is doubtful, the design engineer may decide either not to use the stream or to mix it with other streams. Water used in cooling bearings is a common type of process water.

Cooling tower blowdown is the purge stream from units designed to cool process streams. The concentration of dissolved and suspended solids is often the criterion for frequency of blowdown. Whether blowdown should be used in the system and how and where it should be used are determined by the kind of cooling tower chemical treatment, if any, and by the possible concentration of impurities in the feed water stream, such as particulates that may be washed from the air by cooling tower flow.

2.2.6 Site Conditions

2.2.6.1 Land Availability--

Lime sludge disposal is a major concern in lime FGD systems unless unlimited land is available. Section 2.4 gives a detailed discussion of sludge disposal.

The solids content of untreated sludge is often in the 30 to 40 percent range, and its dewatering characteristics usually are not good. The major constituents of the byproduct sludge are calcium sulfate and calcium sulfite, although the fly ash content may be significant.

Calcium sulfite crystals from lime systems are thin, fragile platelets, usually occurring in clusters or rosettes, which form an open structure with water filling the voids. The rosettes settle well but are difficult to dewater. In most cases, calcium sulfite makes up 20 to 90 percent of the sulfur-containing solids, the remainder being calcium sulfate. The EPRI report, "EPRI/Radian Particle Balance Concept Study," discusses sulfite precipitates. Sludges with large amounts of calcium sulfite generally are not suitable for landfill disposal without additional treatment.[18]

When the sludge is thickened or filtered and subsequently subjected to fixation, solids concentrations in the 70 to 80 percent range can be achieved. Thus the pond volume required to contain untreated lime sludge can be many times as great as that required for the product of sludge fixation. Fixed sludge may be suitable for landfill, whereas untreated sludge would probably remain in the sludge state indefinitely.

Where available land for ponding is limited, sludge treatment and/or fixation may be the only feasible methods of sludge disposal.

2.2.6.2 Soil Permeability--

The pollution potential of sludge liquor seeping into groundwaters is governed by the mobility of the leaching waters; mobility is limited by the coefficient of permeability of the various media through which the leaching water must pass.

The permeation rate of leaching waters through the sludge defines an upper limit to the amount of leachate entering the subsoil. The amount of liquid and the degree of contamination of this liquid jointly determine the pollution potential of any given waste disposal site.

Coal is the source of many contaminants, such as arsenic (As), boron (B), lead (Pb), mercury (Hg), and selenium (Se), which may condense on fly-ash particles or be scrubbed in the absorber.[19]

When major leachate products from untreated sludge were compared with those of oxidized (gypsum) sludge, the calcium, chloride, and magnesium levels were higher in leachate from the untreated sludge; sulfate levels were comparable.

Permeability of the soil at sites proposed for storage of lime sludges is a primary criterion in determining the effect of possible leachates.

2.2.6.3 Ambient Humidity--

The average ambient humidity of the plant site affects the FGD system from the standpoint of overall system water balance. If ambient humidity is high enough to limit evaporation, and if the lime sludge dewaters well, more water may be available for recycle than is needed; periodic discharges into regulated bodies of water may occur.

If the humidity is low, with ample evaporation, additional freshwater is often needed. Abundant freshwater makeup may be desirable for an FGD system if enough water is available.

With high average humidity, the combustion air requires less water to reach saturation temperature, when it is cooled adiabatically. This can strongly affect the water balance of the system by reducing the makeup water requirement.

The major areas of impact of average humidity are large, exposed volumes of process water (such as clarifiers, thickeners, and the sludge pond) and the water balance, as affected by the moisture in the combustion air. The effects of rainfall on makeup requirements are related to the effects of ambient humidity.

2.2.6.4 Rainfall--

The average annual rainfall can have a major impact on the overall water balance of a utility FGD installation. Generally, in an area where the rainfall is high, the evaporation rates are low; and an excess of water may build up in the closed-loop system. This might require periodic discharge of water (opening the "closed loop") or forced evaporation.

Where rainfall is low and the evaporation rate is high, the need for more makeup from outside sources should be expected.

2.2.6.5 Climate--

Climatic conditions should be considered in FGD system design to anticipate problems that might affect operations markedly. Average temperature, wind velocity, precipitation, and other factors may influence the system-wide water balance and other operating parameters.

The major impact of climate will be on decisions relating to enclosure of the unit and the insulation and/or heat tracing of process lines. Critical equipment and control equipment should always be protected.

2.2.7 Regulations

2.2.7.1 SO_2 Emission Standards--

Under the current NSPS, emissions from large boilers are limited to 1.2 lb $SO_2/10^6$ Btu of heat input. A number of states require an even lower maximum SO_2 emission. Under proposed revisions to the NSPS, SO_2 emissions would be limited to a maximum of 1.2 lb/10^6 Btu of heat input and uncontrolled SO_2 emissions would be required to be reduced by 85 percent. The percent reduction requirement would not apply if SO_2 emissions into the atmosphere are less than 0.20 lb/10^6 Btu of heat input.[20]

Currently lime and limestone systems constitute more than 90 percent of the operable FGD systems in the United States. Approximately the same percentage of units under construction are lime and limestone systems, and most units being planned by utilities are of these types.

In Japan, about half the FGD installations use lime or limestone as the SO_2 absorbent. The SO_2 removal capabilities of these predominantly oil-fired units are mostly above 90 percent.

By the end of 1978, the revisions to the NSPS should be complete and prospective FGD system operators will be better able to determine the applicable Federal requirements.

2.2.7.2 Particulate Standards--

The current NSPS limit the outlet particulate emission to 0.1 lb/10^6 Btu of heat input. The proposed revision calls for a maximum of 0.03 lb/10^6 Btu of heat input.

Complying with the proposed particulate standard may require improved mist elimination because the entrained droplets contain both suspended and dissolved solids. An unexpected consequence of excessive entrainment can be that the particulate level of effluent from the absorber may exceed that of the flue gas stream entering the absorber. This is presently under study by EPRI in a scrubber characterization project. Entrained dissolved solids may contribute more to the total solids loading than do the fly ash and other particulates.

2.2.7.3 Plume Visibility Standards--

In most states, statutes limit flue gas stream opacity to 20 percent (Ringelmann No. 1). The Ringelmann test is designed to reflect only particulate loading and not water vapor (the measurement is taken after the water vapor disperses). Particulate loading is controlled by the efficiency of the baghouse, ESP, or wet scrubber prior to the SO_2 absorber, by the ability of the SO_2 absorber to remove incoming particulates, and by the ability of the mist eliminator to reduce carryover.

Where there is no particulate removal ahead of the SO_2 absorber, its ability to remove particulates is critical, and the unit must be designed to remove both SO_2 and particulates. Unless redundant absorber modules are available, there would (where it is allowed) be no effective particulate control when the absorber is partially or completely shut down.

In some states, such as West Virginia, the limit maybe as low as 10 percent. The design engineer should be fully aware of the particulate removal demands on the FGD system, as well as the characteristics of the individual pieces of process equipment, if plume visibility requirements are to be met.

An important restriction in a number of regions is that no visible plume may extend beyond the property line. A very wet plume, however, could well violate such an ordinance, and the FGD system designer should be aware of this possible problem.

2.2.7.4 Water and Land Requirements--

Local, state, or Federal regulations relating to possible water pollution or land use may have major impacts on the design of an FGD system. In some high-density metropolitan areas, such as the State of Massachusetts, even the onsite disposal of fly ash is forbidden -- ash must be removed to disposal sites in nearby states. Disposal of SO_2 absorber sludge is also controlled in other states. Land use regulations must be carefully reviewed for possible constraints that may affect or dictate the design criteria.

Recently, concern has grown about possible contamination of substrata water by trace amounts of heavy metals, such as arsenic, cadmium, and lead, that may be present in the aqueous overflow or leachate from sludge ponds. The leachate problem is currently being investigated. In some cases, the use of pond liners has been successfully tested.

Heavy metals are present in trace amounts in coal. They are volatilized into the flue gas stream and may either condense on the surface of particulates or be washed from the flue gas stream in a particulate scrubber or an SO_2 absorber.

2.2.8 Absorber Type

The SO_2 absorbers used in lime FGD systems, described in detail in Section 4.6, may be classified into five different types: venturi, tray, packed bed, mobile bed, and spray.

The basic design of a venturi absorber is essentially the same as that of a venturi particulate scrubber. The short residence time for intimate contact of absorbing liquid with gas and the cocurrent gas-liquid flow limit the mass transfer from the gas to liquid. A large pressure drop increases gas/liquid contact and therefore increases SO_2 removal. Lengthening residence time to improve gas/liquid contact leads to higher power requirements for flue gas fans and higher operating costs. Chemico offered venturi absorbers in early lime FGD systems.[15] Presently venturi SO_2 absorbers are usually not recommended in lime FGD applications.

A tray absorber consists of a vertical chamber with one or more trays mounted transversely inside to provide multiple countercurrent contact of gas and liquid. The gas velocities should be limited to provide good gas/liquid contact but should be well below flooding condition.[21] At present, none of the utility lime FGD systems uses a tray absorber, mainly because of severe plugging and associated scaling caused by the excessively long residence times of the reactant slurry in the scrubber. Babcock and Wilcox have supplied several perforated tray absorbers for utility limestone FGD systems.

A packed absorber is a vertical column filled with packing, in which there is continuous countercurrent contact of liquid and gas. The maximum permissible liquid and gas rates are determined by the flooding and liquid entrainment characteristics of the packing.[21] Packed absorbers have such good turndown capability that little or no loss in SO_2 removal efficiency occurs at reduced gas loads. Packed absorbers are not widely used in utility FGD systems because of plugging problems and a high fire risk. Research-Cottrell has provided a packed tower absorber at a utility limestone FGD installation.[15]

A mobile bed absorber provides a zone of mobile packing, usually of plastic or glass spheres. In the countercurrent operation of a mobile bed absorber, a highly turbulent action is maintained at each mobile packing stage, ensuring both efficient mass transfer and back mixing.[22]

Plastic spheres are more widely used than marbles (glass spheres). Because of the lower mobility of marbles, the absorber operation becomes less efficient and more susceptible to plugging.

Breakage of hollow plastic spheres has caused plugging in some mobile bed absorbers. The use of solid foam or plastic balls has eliminated the breakage and provided enough turbulence to maintain the self-cleaning action inherent in Turbulent Contract Absorbers (TCA). At the Conesville station of Columbus and Southern Ohio Co., solid plastic spheres were used to replace hollow spheres in the mobile bed absorbers.[23] Mobile bed absorbers have been installed at several lime FGD facilities (see Table 4.6-1).[15] Combustion Engineering offers a marble bed absorber in a lime FGD system. The American Air Filter Co. and UOP (TCA) are leading vendors offering mobile bed absorbers with plastic or foam spheres.[15]

There is a trend away from complicated absorbers to the simplified types such as spray absorbers, which can be classified in three categories: countercurrent, crossflow, and cocurrent.[24] The configuration of the tower may be vertical or horizontal. In a spray absorber, the gas passes through atomized, liquid absorbent droplets. The spray absorber has the advantages of limited internal surface areas, reducing plugging due to scaling. The "openess" of the tower reduces the pressure drop and the energy requirement of the fan. Much of this energy, however, is incorporated into the slurry side to atomize the slurry.

In a vertical spray absorber the gas/liquid flow is usually countercurrent, with the gas entering at the bottom and exiting at the top. The liquid slurry is introduced into the absorber through spray nozzles located throughout the length of the tower. Vertical spray tower absorbers have very low pressure drops and good turndown.[24] They can handle large gas volumes, 500,000 to 1,000,000 acfm in a single vessel.[25] In currently operating facilities, spray tower absorbers are very common in limestone FGD systems, but not in lime FGD systems. The use of spray tower absorbers is on the increase, however, in planned lime FGD systems.[15] Chemico, Combustion Engineering, Combustion Equipment Associates, Pullman-Kellogg, and Peabody Engineering are the leading vendors of spray absorbers.

Crossflow spray absorbers must be horizontal so that the liquid is crosscurrent with respect to the gas flow. Crossflow spray absorbers operate at lower pressure drop, and operation costs may be lower than those of countercurrent spray absorbers.[22] In addition to excellent turndown, the horizontal configuration permits the vertical mist eliminator to be brought in line with the gas flow without any of the complex ducting required by vertical absorbers. However, in horizontal crossflow spray absorbers, the short contact time between the gas and liquid spray must be compensated for by providing an ample absorber volume.[26]

Successful tests were carried out on a 160-MW prototype unit of the horizontal crossflow spray absorber at Mohave Power Station of Southern California Edison Co. Additional successful tests were completed at the Four Corners station of Arizona Public Service.[15] At present no full-scale horizontal spray absorber is in use at any lime FGD facility. One is being constructed on the 825-MW Unit 3 of the Pennsylvania Power's Bruce Mansfield station for the lime FGD system and is scheduled for startup in April 1980.[15] The vendor offering the patented horizontal crossflow (weir) absorber is Pullman-Kellogg.[25]

A cocurrent spray absorber with a vertical configuration is in the development stage, as described in an EPRI report "Cocurrent Scrubber Evaluation TVA's Colbert Lime/Limestone Wet-Scrubbing Pilot Plant." EPRI is funding the evaluation of a 10-MW cocurrent scrubber at the Shawnee Test facility in Paducah, Kentucky.

2.2.9 Waste Slurry Disposal

The byproduct generated by an FGD system depends on the absorbent (lime), the flue gas characteristics, and the mode of operation of the scrubber. The major constituents of the byproducts are calcium sulfate and calcium sulfite. The ratio of sulfite to sulfate depends on the extent of oxidation, which is in turn mainly a function of slurry liquid composition and the free oxygen content of flue gas. This is discussed more fully in Section 2.4.

In general, byproduct sludges may contain less than 5 or as much as 10 percent fly ash, depending on the amount of fly ash removed from the flue gas prior to the scrubbing process.

If the primary constituent of the sludge is calcium sulfite, generally in the form of thin platelets, it is extremely difficult to dewater, as explained in Section 2.2.4.[18] More information concerning sludge characteristics is given in an EPRI report "Full Scale Scrubber Sludge Characterization Studies." Solids content of sulfite scrubber sludge ranges from 15 to 40 percent upon settling. Thickened and chemically fixed sludge contains 40 to 70 percent solids. The solids content of untreated calcium sulfite sludge is low because water is trapped in the sludge by the platelet structure of the sulfite crystals. This type of sludge affects FGD system design because more land disposal area and makeup water are required. Except where makeup water is a scarce commodity, a high water makeup rate offers a side benefit in that it allows the use of more freshwater in the mist eliminator wash and other areas of FGD system.

Increased oxidation of the sulfite portion of the sludge can be accomplished by bubbling air into the solution in the reaction tank at specified pH levels.[27] Work by researchers at the TVA's Shawnee plant has demonstrated almost complete conversion of the sulfite to sulfate. The rod-shaped sulfate crystals dewater much more readily.[18] The effects of this on FGD system design is that less land disposal area is needed and the sludge may be used as a landfill. Less water would leave the system as interstitial blowdown, which may increase concentration of dissolved solids in the system.

The thickening ability of a sludge may be increased by adding a settling aid. In a gravity thickener, a settling aid (such as about 30 ppm of acrylamide copolymer) may increase solids concentration in the thickener underflow and reduce settling time. Depending on the sulfite/sulfate ratio and crystal size, thickening may yield a slurry of 25 to 50 percent solids. Vacuum filtration may yield a 45 to 70 percent solids material. Again, the impact on FGD system design is to reduce ponding requirements, improve the likelihood of this sludge being used as landfill, and reduce possible water pollution problems.

Chemical fixation of the thickened sludge can be accomplished by one of several proprietary processes, such as those of IU Conversion Systems, Dravo, or Chemifix.[18] The primary criterion for fixation is the intimate mixing required for proper disposal of the stabilizing agent and complete wetting of fly ash. The resulting fixed sludge may have from 60 to 80 percent solids. Often this sludge is of landfill structural quality. The effects of FGD system design include higher cost for sludge handling and fixation, minimum possibility of water pollution problems, the need for only minimum sludge pond area because of the landfill properties of the sludge, and minimum impact on the system water balance.

2.2.10 Redundancy

A designer's attitudes toward redundancy are influenced by management policies regarding expenditures for installed spare capacity and by the regulatory constraints on FGD system operation.

Operating an FGD system properly and reliably while accomplishing the mandated SO_2 removal may well entail the installation of spares for the major process equipment, such as critical pumps, absorbers, wet scrubbers (if any), and slakers. The degree of redundancy is an engineering decision. The capital expenditure required for a spare absorber module can be significant. The number of spares that may be needed depends on the number of operating units, the reliability of each unit, and the impact on overall operation if the unit is not online (e.g., if an absorbent to other stages may be able to compensate). Furthermore, allowance for in-process storage or surge tanks may permit shutdown of some pieces of major process equipment for maintenance or repairs.

A recent draft of the proposed NSPS for coal-fired utility boilers recommends that exemptions for malfunctions not be allowed under the proposed SO_2 standards. Further, it concludes that spare FGD modules should be installed and that when a malfunction occurs where emission requirements cannot be met, the operator should derate the boiler or shut it down. The power gap would be closed by increasing the load on other generating units within the system or by the purchase of outside power.

The FGD system designer should be aware of how to minimize redundancy, but should consider both the legal and financial ramifications of the need for redundancy.

2.2.11 Method of Reheat

There are basically six alternatives with respect to flue gas reheating: no reheat, in-line reheat, direct-fired reheat, indirect hot air reheat, flue gas bypass, and exit gas recycle reheat. Much of this information on reheat is detailed in Section 4.11. The reasons for reheat are to prevent corrosion caused by condensation, to prevent a visible plume, and to attain the desired plume rise; however, corrosion of the reheat equipment is a significant problem. More information is given in an EPRI report, "Stack Gas Reheat for Wet Flue Gas Desulfurization Systems."

Although the no-reheat option may seem to exert zero impact on daily operating costs, there is a high probability that the saturated flue gas stream will reach its dew point, with condensation on material surfaces, and that the condensate will absorb SO_2 to form a corrosive, acidic liquid downstream from the SO_2 absorber. Therefore, the design and cost implications are that the ducting, the stack, and fan must be as corrosion-proof as possible; that equipment will need intensive maintenance and earlier replacement; and that daily operating cost will be lower because no reheat cost is incurred. Design of the downstream equipment for corrosion prevention/reduction is critical with the no-reheat option.

In-line reheat often involves the use of steam inside banks of tubes designed for maximum heat transfer to impart the temperature increase required to prevent condensation. High-pressure hot water (250° to 350°F at 15 to 120 psig) may also be used. The design considerations are all aimed at corrosion resistance on the tube surfaces. Carryover of liquid from the mist eliminator may lead to solids deposition on the tubes as the liquid dries, and corrosion may take place beneath these deposits. In addition to use of corrosion-resistant materials of construction, soot blowers are sometimes used to reduce solids deposits.

With in-line steam reheat, operators of some FGD systems report better corrosion protection by leaving the steam on at all times. Again, materials of construction are chosen on the basis of projected flue gas stream conditions and chemical composition. Decisions regarding materials of construction and mode of operation (on/off or "always" on) are economic ones. The economics are affected by whether the steam used for reheat causes derating of the turbine or whether it comes from a separate steam boiler.

With direct-fired reheat, oil or gas is burned in the flue gas stream. The cost of fuel needed for this practice is often significantly higher than that of steam reheat, especially if the steam requirement exceeds boiler capacity. Again, corrosion of the exposed metal surface is of concern, although the exposed area is much less. Air leakage greatly accelerates corrosion rates; operators of some FGD systems believe that prevention of leaks and rapid repair are critical to maintaining the reheat equipment.

Because of corrosion of reheat equipment in the flue gas stream, some designers have opted for a more expensive but more reliable means of achieving the desired temperature increase. In indirect hot air reheat a fan brings in outside air, which is heated by direct or indirect means (gas/oil or steam) and is then mixed with the flue gas stream. The volume of gas to the stack is increased by the hot air volume, and the cost is higher; however, maintenance problems and the possibility of emergency shutdown because of reheat failure are greatly reduced.

Under the present NSPS, some systems can bypass a portion of the flue gas stream from the SO_2 absorption train. This stream can be used to reheat the portion of the flue gas stream that has been cleaned. If this practice provides compliance with the applicable emission standards, it is the least expensive method of reheat. The draft of the proposed NSPS calls for 85 percent removal of SO_2 over a 30-day period, with a maximum allowable emission of 1.2 lb $SO_2/10^6$ Btu heat input. If the emission level is as low as 0.2 lb $SO_2/10^6$ Btu, the percent removal requirement will not apply.[14] Should this proposal become law, use of the bypass reheat option will be extremely difficult.

Reheat by recycling the exit gas involves removing cleaned, heated flue gas from the stream before it enters the stack and further heating this side stream to the temperature needed for recycling to the main stream at the absorber outlet, where it reheats the whole stream. In contrast to indirect hot air reheat, the total gas flow is not increased and reheat is less influenced by ambient air conditions. This mode of reheat has not been installed on a utility boiler.

These reheat methods raise the temperature of the flue gas stream in most systems from the adiabatic saturation temperature, about 125°F, to approximately 175°F. When heated gas streams are mixed with the flue gas stream, air or recycled flue gas must be at about 400°F to achieve reheat.

To prevent a visible plume, reheat of the flue gas usually depends on the ambient temperature and relative humidity.

2.2.12 Degree of Instrumentation

The principal concern in instrumentation is pH control of the absorbent slurry to achieve maximum SO_2 removal. To this end, feedback instrument loops were initially used in many systems; however, because of scaling of the probes, lime blockage, breakage of probes, and many other problems, many operators have resorted to manual grab samples for control of lime feed and SO_2 emissions. As a result, lime usage often is well over that required, and SO_2 emissions are higher than those provided in design.

As operators gain understanding of scaling tendencies and learn where pH probes may be placed for best control and maintenance, they are returning to automated control.

Sophisticated pH systems are needed to comply with increasingly strict SO_2 emission regulations. As a side benefit, lime usage and overall control are improving. An advanced pH system utilizes the feed forward/feedback concept. An alternative is to measure the SO_2 concentration directly, although instrument problems have arisen in the severe service. The flue gas stream can be monitored at the inlet for SO_2 concentration and flow volume and at the absorber exit to determine SO_2 removal.

A method being tried for control of the absorbent recycle volume is to regulate pump output as the system gas flow load fluctuates.

2.2.13 Mist Eliminator Configuration[17]

Detailed information concerning mist elimination is given in Section 4.7.

Mist eliminators are designed to remove entrained water droplets, which carry both suspended and dissolved solids. Efficient removal of the droplets reduces problems with particulate emission and plume opacity; it also reduces the probability of corrosion associated with aqueous acidic solutions and the likelihood of scaling caused by deposition of solids on the metal surfaces of such parts as reheaters, fans, and ducts.

The variables in mist eliminator design include horizontal or vertical configuration, the use of bulk separation and knockout devices, the number of passes, the number of stages, the distance between stages, and the type of mist eliminator (continuous or discontinuous, chevron, or radial).

Horizontal mist eliminators have several disadvantages. The flue gas stream flows upward through the apparatus, and the droplets collected by the mist eliminator fall back through the gas flow, increasing the possibility of reentrainment. They also remain on the blade surface longer because of the action of the gas flow, increasing the probability of scaling or plugging. Difficulties also occur in the mist eliminator wash because all wash falls back into the absorber and because wash cannot be done longitudinally, which is the most effective way.

In vertical mist eliminators the gas flow is horizontal. Hook sections are used on the baffles to prevent reentrainment, and droplets are collected in a tray beneath the vanes. These units may be operated at higher gas velocities than the horizontal type without reentrainment. The vertical type is the most widely used in Japanese FGD installations.

Bulk entrainment separators and knockout devices are designed to remove large liquid droplets before the gas stream enters the mist eliminator. Bulk entrainment separators often take the form of an expansion area in which velocity is reduced and the droplets are removed by gravity. Some knockout devices permit the collection of wash water for reuse.

The number of passes indicates the number of direction changes the gas stream must make before it exits the mist eliminator. Often, the greater the number of passes, the greater the efficiency; however, because of possible plugging, three passes are most common in lime FGD units and provide good collection efficiency with adequate washability.

Both one- and two-stage mist eliminators are common. A single-stage unit often operates in conjunction with a bulk entrainment separator. Two-stage units allow the use of more wash water. The second stage is unwashed and collects mist from the washing of the first stage as well as from normal entrainment.

The chevron baffle comes with continuous or discontinuous baffles. Entrained liquid is forced to make abrupt changes in direction, causing inertial impaction on baffle walls. Both sharp and smooth vane bends are used, but sharp bends predominate. Continuous chevron design is often selected because it provides greater strength at lower cost. Pressure drop is not a consideration for either chevron design.[17]

The radial vane mist eliminator is a cyclonic separator whose curved vanes redirect the gas stream from the vertical path to the horizontal path, which is aimed at the vessel wall. Heavier liquid droplets and solid particles are attracted toward the vessel wall, where they impact and are collected. The pressure drop of radial vane units is much greater than that of the chevron type. For mist elimination, however, radial vane units have not operated as well as chevron units.

Mist eliminators may be constructed of 316L stainless steel (strong, rigid, corrosion-resistant, not temperature-sensitive, but heavy and more expensive than other materials), fiberglass reinforced polyester (FRP) (corrosion-resistant and light, but pressure- and temperature-sensitive, may become brittle), or Noryl thermoplastics (inexpensive and light, but temperature-sensitive). Despite its drawbacks, FRP is the predominant construction material for mist eliminators.

2.2.14 Losses Throughout the System

An often-overlooked design objective is to minimize process losses. Concentration on this goal begins with lime delivery and continues through slaking, slurry dilution, operation of the reaction/hold tank beneath the SO_2 absorber, and sludge handling (until the sludge is delivered to the pond). This effort also applies to minimizing water losses from the sludge pond.

As the lime is delivered, the air from pneumatic unloading entrains lime as it exits the storage silo. An excellent way of recovering this lime and reducing pollution potential is to have two cyclone separators in series or a baghouse for particulate removal. This arrangement can often remove over 99 percent of the airborne solids. The recovered lime is returned to the silo.

The lime delivery conveyor belt or screw conveyor system should be covered, tightly sealed, and maintained at a slightly negative pressure to avoid losses. The entrained lime is recovered and discharged into the lime storage silo.

The area around the slaker should have washdown facilities from which the water goes into a collection sump, where large particles can be separated and the slurry can be recycled for dilution. Washdown stations and slurry collection pumps also are desirable around the slurry dilution tanks, the absorber reaction or hold tanks, and major process pump areas.

2.2.15 Process Layout

Good process layout calls for a balance between minimizing the distance between the major process operators and allowing adequate space in the ground and overhead for process maintenance and instrumentation.

It is desirable to minimize the distance between lime storage, lime slaking, and lime slurry preparation areas. The distance from the makeup slurry tank to the reaction/hold tank beneath the absorber is not critical. The distance from the SO_2 absorber and reaction/hold tank to the purge thickener should be minimal, but it is not critical.

Although each process supplier has his own preference regarding location of equipment, it is generally desirable to locate the reaction/hold tank directly below the SO_2 absorber. Individual pumps supply slurry to each header system. Mist eliminators are most often of the horizontal type, directly atop the SO_2 absorber.

2.2.16 Materials of Construction

Materials of construction and the mechanics of corrosion attack are discussed in detail in Section 4.12.

The most common forms of corrosion in FGD systems are crevice corrosion, intergranular corrosion, and erosion-corrosion. Early experience with FGD systems taught designers that the particulate scrubber performs best if it is lined, since the mixture of chlorides, sulfuric acid, sulfurous acid, and particulates attacks any unprotected steel surface. The absorber can be constructed of carbon steel with a liner or of alloy steel without a liner. The debate over which is superior continues.

When a wet particulate scrubber is part of the FGD system design, the materials of construction are a carbon steel for the shell and 316 or 316L stainless steel for the venturi throat. The internal liner, which completely covers the carbon steel shell, may be of natural or neoprene rubber, flaked glass (such as Heil 490 or Ceilcote 103 or 151), or Precrete. Natural and neoprene rubber are the most popular liners, usually with excellent operational records.

The SO_2 absorber should be constructed from corrosion-resistant materials or carbon steel that is coated with plastic material such as flaked glass or is rubber lined. Most common are 316L stainless steel and neoprene-lined carbon steel absorbers. Hastelloy G, Inconel 625, or 316L stainless steel are used for some exposed internal parts.

The mist eliminator should be made of FRP or stainless steel (316L) for corrosion resistance.

The reheat equipment may be constructed of anything from carbon steel to exotic alloy steel, depending on the system supplier's policies, the flue gas composition, the expected volume and composition of carryover from the mist eliminator, and other factors.

The fans may be constructed of anything from carbon steel to Inconel, depending on whether the fan is operated dry or wet, the expected chemical composition of the gas and/or liquid, and the system supplier's preference.

Pumps and recirculation and transfer piping may be made of rubber-lined (natural or neoprene) carbon steel or alloy steel.

Lime slakers are primarily constructed of carbon steel.

Tanks may be carbon steel, FRP, rubber-lined carbon steel, or 316 or 316L stainless steel.

Selection of a suitable stack lining material is still in question, partly because everything used to date has been less than successful. Recent hypotheses blame fluorides for the failure of some plastic coatings. Sprayed-on coatings often show pinholes where corrosion starts; the corrosion accelerates until the whole lining fails or comes off in sheets or large pieces.

2.2.17 Chemistry

2.2.17.1 pH Gradient--

As the lime slurry enters the SO_2 absorber, the pH is often in the 7.5 to 8.5 range. When the absorbent reacts with the SO_2, the pH drops as the slurry becomes more acidic. The pH may be in the 4.5 to 6 range as the slurry leaves the absorber.

Johnstone reported in 1935 that the logarithm of the equilibrium vapor pressure of SO_2 over lime solution was inversely proportional to the pH of the solution. This results in lower SO_2 equilibrium vapor pressure at higher (more alkaline) pH. Test work recently conducted at the Shawnee test facility of TVA showed higher SO_2 removals at higher pH with constant L/G ratios. The disadvantage of increasing the pH is that the excess lime required for this mode of operation increases the cost of operation and the tendency for scale formation.[13]

2.2.17.2 Sulfite to Sulfate Oxidation--

The calcium sulfite in the absorbent stream may react with free oxygen and form calcium sulfate, which has no SO_2 absorbing value. The oxygen may result from high excess air used in firing the coal in the power boiler, or it may enter as air leakage (in the preheater or holes in ducting).

In FGD sytems design, the excess air for fuel firing should be reduced to the lowest safe level; in system operation, any holes that appear in the flue gas ducting should be repaired.

The sulfite purge from the absorber can be oxidized in a separate reaction tank to convert the sulfite to sulfate, producing a crystalline structure that may be dewatered much more easily. This is done either in a separate tank or in a separate scrubbing stage where low pH can be maintained to encourage oxidation.

2.2.17.3 Chloride Balance--

The chloride level in the operating mode practiced at most FGD systems is maintained through losses of chlorides in the interstitial water in the calcium sulfite/sulfate sludge. Theoretically, the chloride steady-state level in FGD system operations may reach 30,000 ppm; reported values rarely exceed 6,000 ppm.

Only one U.S. unit controls absorber purge on the basis of chloride content, whereas this is a common practice at many Japanese units because of the adverse effect of chloride in wallboard production. The major concern with chlorides is corrosion of the wet particulate scrubber, and of exposed steel surfaces on the absorber. The damage resulting from chloride attack is well documented in U.S. FGD experience.

The chlorides originate in the coal and are volatilized as the coal is burned. They are removed when they contact aqueous streams. Chlorides also decrease the effect of magnesium and should therefore be minimized when magnesium is added purposely to a scrubbing system. Notwithstanding these factors, a calcium chloride system has been used for SO_2 removal.

2.2.17.4 Liquid-to-gas Ratio--

The L/G ratio expresses the lime slurry flow (gallons) in the absorber per 1000 acfm of flue gas flow at absorber conditions. Increasing the L/G ratio enhances liquid mass transfer at the interface because of increased turbulence and better gas distribution, which increases the mass transfer coefficient. A high L/G ratio also provides more driving force because of the lower sulfite buildup in the slurry per pass.

The L/G ratio also affects residence time of the gas stream in the absorber, which in U.S. FGD units ranges from 3 to 9 s.

In mobile bed absorbers the mobile packing has a major impact on the liquid/gas interface; at the Shawnee test unit of TVA, mobile bed packing had more of an effect on SO_2 removal than did gas velocity or absorber residence time. With a mobile bed absorber, the L/G approaches 80 gal overall. L/G ratios in normal mobile bed absorber operation range from 30 to 50. This range is usually well below flooding conditions in a mobile bed absorber. (A flood condition occurs when enough slurry is held up in the scrubber to prohibit the passage of flue gas through the absorber without ensuring a pressure drop considerably higher than designed.)

Because there is no flooding problem in spray towers, the power required for pump operation may be a constraint. Liquid-to-gas flows of 60 to 100 gal/1000 acfm have been used, although normal operating values are from 60 to 80.

2.2.17.5 Point of Fresh Slurry Addition--

In the past, the diluted fresh lime slurry was added at several places in the absorbent recirculation loop. The two major points of addition were in the piping recirculating to the absorber and in the reaction/hold tank beneath the absorber. Because chemical reactions occurred in the piping, on the top tray, in the first rows of balls or marbles in a mobile bed absorber, and in other locations, the addition of fresh makeup slurry in the recirculation piping has been discontinued.

All the major lime FGD system suppliers now add the makeup lime slurry to the reaction/hold tank. Care must be taken in slurry addition, since this can directly affect the precipitated particle size. An EPRI report, "EPRI/Radian Particle Balance Concept Study," discusses in detail the proper point of lime feed addition.

2.2.17.6 Scaling--

Early lime FGD systems were generally operated without attention to the basic methods of scale-prevention: high L/G, high crystal content in the slurry, and adequate retention time outside the scrubber. After discovery of massive deposits of hard sulfate scale and also some deposits of softer sulfite scale, steps were taken to control scaling. Deposits also occur at the wet/dry interface within the wet particulate scrubber or the SO_2 absorbing vessel. These deposits are mixtures of fly ash, sludge, and sometimes soluble salts.

Scaling occurs by three basic mechanisms: (1) by nucleation on equipment surfaces with subsequent growth transformation of soft deposits (sulfite) to gypsum (sulfate) scale, (2) by pH excursions into the lower ranges, and (3) by physical drying.

Precipitation of calcium sulfate normally occurs on existing gypsum crystals, which provide an excellent nucleation site. A higher slurry solids content and smaller slurry particle size increase the number of nucleation sites in the slurry (as opposed to the internal surface area of the scrubbing vessel) and decrease the likelihood that gypsum scale forms on the scrubber internals. Therefore, a slurry solids content of 15 percent provides the system with more resistance to scale formation (depending on type of solids) than a slurry solids content of 5 percent.

The effect of slurry particle size distribution can be even more important than slurry solids content. When lime slaking occurs, for example, the calcium hydroxide crystals produced range in size from 1 to about 5 μm. The corresponding mean particle size of scrubber slurry when using lime reagent will range from 10 to 40 μm, depending on the operating conditions.[28]

Scale formation caused by pH excursions has been less pronounced with lime reagent than with limestone reagent because the pH is at a higher level when lime is used. The degree of calcium sulfite oxidation to calcium sulfate is reportedly reduced when the pH level is increased. The tendency of slurry to form high levels of dissolved calcium and sulfate ions is thus suppressed by use of lime reagent at higher pH levels. When a pH excursion to 4 to 4.5 occurs, regardless of the type of reagent, severe and rapid formation of calcium sulfate scale can arise. At one unit severe scale formation occurred on the bottom level of perforated distribution trays as a result of a pH variation initiated by a switch to high-sulfur coal. The pH of the absorber slurry is at its lowest level when the slurry reaches the bottom level of distribution trays in the absorber.[28]

Soft deposits of scrubber slurry tend to form in all regions of separated gas flow and in quiescent zones inside the absorber vessel where flow is insufficient. The characteristics of soft deposits are usually as follows:

- A large fraction of the deposit consists of calcium salts, including calcium sulfite.
- The wet surface of the soft deposit is exposed to a gas stream containing SO_2.

- Very low rates of movement of liquid occur in the interstices between the mechanically deposited soft solids.

Under the conditions specified, it is only a question of time before the soft deposit is cemented together by calcium sulfate precipitation into a mass of hard, chemically bonded scale. The SO_2 absorbed into the liquid on the wet, exposed surface of the deposit reduces the pH of the interstitial liquid at the surface. This low pH liquid can diffuse into the soft deposit, dissolving calcium sulfite and/or calcium carbonate solids along the way. Oxygen dissolves into the liquid and reheats with sulfite or bisulfite to form sulfate ion. The dissolved calcium ion concentration continues to build up, because of the low rates of movement in the interstitial liquid, until the liquid is eventually supersaturated with calcium sulfate. Finally, calcium sulfate precititates on the existing solids in the soft deposit, bridging the gaps and "gluing" the entire structure together with hard gypsum scale.

This slow but continuous precipitation of calcium sulfate causes a transformation to hard scale in a matter of days or weeks, depending on the reagent type, dissolved solids content in the slurry, and specific conditions (i.e., pH level and SO_2 and O_2 concentration in the gas stream) at the location of the soft deposit.

Scale caused by physical drying can occur at a wet/dry interface upstream from the scrubber and also as a result of repeated outages, during which the scrubber internals dry out. In both cases, the mechanism involves repeated cycles of wetting and drying, during which the physical deposition of dissolved salts during the drying cycle helps bond the normally soft deposit into a much harder deposit. In an absorber operation, the exact location of the wet/dry interface is primarily a function of gas flow rate; the interface can move back and forth with boiler load, thus creating the wetting and drying cycles necessary for the formation of dried scale.

2.2.17.7 Oxidation of SO_2 to SO_3--

As coal is burned, sulfur in the coal is volatilized and oxidized to form SO_2, and about 3 percent of the SO_2 is further oxidized to sulfur trioxide (SO_3). Some iron compounds and vanadium compounds act as catalysts for the conversion of SO_2 to SO_3 in the presence of free oxygen (excess air) at temperatures that occur within a boiler. About 60 percent of the SO_3 is absorbed in the wet particulate scrubber and the SO_2 absorber, according to work done at the Shawnee test facility of the Tennessee Valley Authority (TVA).

2.2.17.8 NO_x Interferences--

In one major case, Wood River Unit 4 of Illinois Power, NO_2 interference was noted. When the FGD unit was put on-stream, a visible plume remained. Since the FGD system removed more than 99 percent of the particulates and since the plume had a characteristic brownish tint, NO_2 was surmised to be the culprit. The absence of particulate eliminated the masking effect that normally made the NO_2 emission unnoticeable.

2.2.17.9 Stoichiometric Ratio--

Newer lime systems use 1.10 to 1.15 moles of lime per mole of SO_2 removed, although some systems go below 1.10. A range for most lime-based FGD units in the United States is 1.05 to 1.30 moles of lime per mole of SO_2 removed.

The higher the stoichiometric ratio, the higher the operating cost, because more usable lime may be lost. A higher stoichiometric ratio may be required if there are wide variations in the inlet SO_2 loading, so that SO_2 removal may remain at or above the mandated levels. The higher stoichiometric ratio increases the SO_2 removal efficiency of the scrubbers.

2.2.17.10 Lime Utilization--

If the stoichiometric ratio is based on SO_2 removed, the utilization of lime is the inverse of the ratio. As the stoichiometric ratio increases, the utilization of lime decreases. Utilization is a function of mass transfer efficiency and degree of reaction in the reaction tank. Good utilization can be attained with good mass transfer, sufficient recycle tank residence time, and extraction of the purge from the slurry recycle lime. Some lime-based FGD units in the United States report 88 to 99 percent utilization of lime.

2.2.18 Process Approximations and Design Data

This section gives information in tabular forms for process approximations. It often is unnecessary to calculate a value when all that is required is a rough estimate, e.g., an estimate of the acreage required for disposal of sludge for a power generating unit of a given size. Table 2.2-10, summarizes approximate process values for coals of low, medium, and high sulfur content.

Table 2.2-10. PROCESS APPROXIMATIONS

	Sulfur content of coal, % 0.6	3.4	5.0
Coal analysis			
Moisture, %	25.7	4.18	3.97
Volatile matter, %	34.5	37.64	38.89
Fixed carbon, %	32.0	46.54	40.65
Ash, %	7.2	8.24	11.47
Sulfur, %	0.6	3.40	5.02
Heating value, Btu/lb	8250	12,920	12,230
lb SO_2 basis			
dscf flue gas/lb SO_2	9485	2388	1535
acf 300°F flue gas/lb SO_2	16,830	3700	2372
lb CaO required/lb SO_2 (1.1 times stoichiometric requirement)	0.96	0.96	0.96
lb dry sludge produced/lb SO_2	2.35	2.35	2.35
Makeup water, gal/lb SO_2	4.9	1.36	0.8
Ton of wet coal basis:			
dscf flue gas/ton	227,700	325,600	308,200
acf 300°F flue flue gas/ton	403,950	503,200	476,400
lb SO_2/ton	24	136	200
lb CaO required/ton	23.1	131	192
lb dry sludge produced/ton	56.4	320	470
Makeup water, gal/ton	119	186	161

(continued)

Table 2.2-10. (continued)

	Sulfur content of coal, % 0.6	3.4	5.0
MW basis			
dscfm flue gas/MW	2300	2100	2100
acfm 300°F flue gas/MW	4080	3246	3246
lb SO_2/h per MW	14.4	52.8	82.2
lb CaO/h per MW	13.8	51.0	78.6
lb sludge (dry)/yr per MW	265,000	980,000	1,500,000
Makeup water gal/min per MW	1.2	1.1	1.1
Million Btu basis (input)			
dscf flue gas/million Btu	13,800	12,600	12,600
acf 300°F flue gas/ million Btu	24,480	19,475	19,475
lb SO_2/million Btu	1.45	5.26	8.2
lb CaO/million Btu	1.40	5.05	7.9
lb (dry) sludge produced/million Btu	3.4	12.4	19.3
Makeup water, gal/ million Btu	7.2	6.6	6.6

REFERENCES

1. PEDCo Environmental, Inc. Analysis of the Effect of Coal Properties on Furnace/Boiler Combustion Characteristics. April 1975, pp. 1-1 through 1-4.

2. PEDCo Environmental, Inc. Analysis of the Effect of Coal Properties on Furnace/Boiler Combustion Characteristics. April 1975, pp. 1-5 through 1-7.

3. Combustion Engineering Handbook, 1978, pp. 24-27.

4. PEDCo Environmental, Inc. Analysis of the Effect of Coal Properties on Furnace/Boiler Combustion Characteristics. April 1975, pp. 4-20 through 422.

5. Szabo, J.F., and R.W. Gerstle. Operation and Maintenance of Particulate Control Devices on Coal-fired Utility Boilers. EPA-600/2-77-129, July 1977, pp. 2-24 through 2-30.

6. PEDCo Environmental, Inc. Analysis of the Effect of Coal Properties on Furnace/Boiler Combustion Characteristics. April 1975, pp. B-3, 4, 7, 8.

7. Szabo, M.F., and R.W. Gerstle. Operation and Maintenance of Particulate Control Devices on Coal-fired Utility Boilers. EPA-600/2-77-129, July 1977, pp. 2-49 through 2-55.

8. Szabo, M.F., and R.W. Gerstle. Operation and Maintenance of Particulate Control Devices on Coal-fired Utility Boilers. EPA-600/2-77-219, July 1977, pp. 2-26 through 2-45.

9. PEDCo Environmental, Inc. Analysis of the Effect of Coal Properties on Furnace/Boiler Combustion Characteristics. April 1975, pp. 4-26 through 4-30.

10. Devitt, T., R. Gerstle, L. Gibbs, S. Hartman, R. Klier, and B. Laseke. Flue Gas Desulfurization Systems Capabilities for Coal-fired Steam Generators. PEDCo Environmental, Inc., Contract No. 68-02-2603, November 1977, pp. 3-33, -38, -39, -44, -45, and -82.

11. Bechtel Corporation. Flue Gas Desulfurization Implications of SO_2 Removal Requirements, Coal Properties, and Reheat (Draft). July 1977.

12. Gibbs, L.L., D.S. Forste, and Y.M. Shah. Particulate and Sulfur Dioxide Emission Control Costs for Large Coal-fired Boilers, PEDCo Environmental, Inc. EPA Contract No. 68-02-2535, Task No. 2, October 1977.

13. Battelle Columbus Laboratories. Stack Gas Reheat for Wet Flue Gas Desulfurization System. EPRI Report, November 1976.

14. Flue Gas Desulfurization Using Fly Ash Derived from Western Coals. EPA-600/7-77-07b, July 1977, p. 4.

15. Laseke, B.A. Environmental Protection Agency Utility FGD Survey, December 1977-January 1978. EPA-600/7-78-051s, March 1978.

16. Lime Handling, Application, and Storage. National Lime Association, 1949. pp. 49, 50, and 56.

17. Conkle, H.M., H.S. Rosenberg, and S.T. DeNova. Guidelines for the Design of Mist Eliminators for Lime/Limestone Scrubbing Systems. EPRI Report No. FP-327, pp. 2, 50, 58, 61, 56, 72, and 74.

18. Michael J. Baker, Inc. State-of-the-Art of the Flue Gas Desulfurization Sludge Fixation. EPRI Report No. FP-671, January 1978.

19. Disposal and Use of Byproducts from FGD Processes. In: FGD Symposium. EPA-650/273/038, May 1973.

20. Federal Register, Part V. Department of the Interior, September 19, 1978.

21. Treybal, R.E. Mass Transfer Operations. Ch. 6. McGraw-Hill Book Co., New York, 1968.

22. Bethea, R.M. Air Pollution Technology. Van Nostrand Reinhold Co., 1978.

23. Melia, M., M. Smith, W. Fischer, and B. Laseke. Environmental Protection Agency Utility FGD Survey, June-July 1978. EPA Contract No. 68-01-4147, PEDCo Environmental, Inc., Cincinnati, Ohio.

24. Slack, A.V. Design Considerations in Lime-Limestone Scrubbing. Paper presented at Second Pacific Chemical Engineering Congress, Denver, August 1977.

25. Bendor, F., J. Englick, and A. Saleom. Flue Gas Desulfurization in Venturi Scrubbers and Spray Towers. Paper presented at Second Pacific Chemical Engineering Congress, Denver, August 1977.

26. Edward, W.M., and P. Huang. Mass Transfer in the Kellogg-Weir Air Control System. Paper presented at National AIChE Meeting, Houston, March 1977.

27. Haas, J.C., and W. Lombardi. Landfill Disposal of Flue Gas Desulfurization Sludge. Combustion Engineering Power Systems. Paper presented at NCA/BCR Conference and Expo III, October 19-21, 1976.

28. Jones, D.G., A.V. Slack, and K.S. Campbell. Lime/Limestone Scrubber Operation and Control Study. EPRI No. RP630-2, April 1978.

CONTENTS

2.3 PROCEDURES FOR CALCULATING A MATERIAL BALANCE

Page

2.3.1 Introduction 2.3-1

2.3.2 Process Description 2.3-1

2.3.3 Sample Calculations 2.3-21

2.3.4 Boiler Furnace Material Balance (Step 1) 2.3-25

- 2.3.4.1 Ash Balance 2.3-25
- 2.3.4.2 Carbon Balance 2.3-28
- 2.3.4.3 Chloride Balance 2.3-29
- 2.3.4.4 Theoretical Amount of Air Required for Combustion 2.3-29
- 2.3.4.5 Moisture Balance 2.3-31
- 2.3.4.6 Nitrogen Balance 2.3-34
- 2.3.4.7 Oxygen Balance 2.3-36

2.3.5 SO_2 and Particulate Material Balance (Step 2) 2.3-38

2.3.6 Slurry Preparation Material Balance/Lime Requirement (Step 3) 2.3-40

- 2.3.6.1 Slaker 2.3-42
- 2.3.6.2 Slurry Feed Tank 2.3-44

2.3.7 Scrubber Material Balance (Step 4) 2.3-45

- 2.3.7.1 Waste Slurry Calculation 2.3-45

2.3.8 Water Balance (Step 5) 2.3-55

2.3.9 Information on Several Operable Lime Absorber Systems on Utility Boilers 2.3-57

- 2.3.9.1 Bruce Mansfield Station, Pennsylvania Power Co. 2.3-57
- 2.3.9.2 Cane Run No. 4, Louisville Gas and Electric 2.3-63
- 2.3.9.3 Conesville No. 5, Columbus and Southern Ohio Electric Co. 2.3-67

CONTENTS (Continued)

2.3.9.4 Green River Station, Kentucky Utilities 2.3-73
2.3.9.5 Paddy's Run Station, Louisville Gas and Electric 2.3-80
2.3.9.6 Phillips Power Station, Duquesne Light Co. 2.3-86

2.3.10 Conversion Factors 2.3-91

References 2.3-100

2.3 PROCEDURES FOR CALCULATING A MATERIAL BALANCE

2.3.1 Introduction

This section is intended to aid a design engineer in making a material balance for a particular plant site. A set of conditions is specified, and a material balance is developed in stepwise fashion. Details concerning process approximations, estimating techniques, and design data are given in Tables 2.3-1 through 2.3-3, and Figures 2.3-1 through 2.3-11.

The process selected for this illustration, and general aspects of the process material balance are described in Section 2.3.2. Efforts were made to simulate operating plants in selecting these data. Some of the process chemistries are simplified for the purpose of illustration. A full sample calculation is shown in Section 2.2.3.3.

2.3.2 Process Description

A flow diagram for the example lime scrubbing FGD process (Example 1) is presented in Figure 2.3-12. In this example, 420,000 lb/h of coal is fired to generate approximately 500 MW (gross) of electricity. Although an FGD system of this size usually consists of several modules, it is assumed in these stream calculations that all the modules are combined.

The major components of coal are carbon, oxygen, nitrogen, hydrogen, sulfur, free moisture, and ash. A minor, but important, component is chloride because of the corrosion effect. A typical coal analysis is presented in Table 2.3-4. The high heating value (HHV) of this coal is 11,150 Btu/lb; ash consists of 80 percent fly ash and 20 percent bottom ash.

The mechanisms of coal combustion are complex, and discussion is beyond the scope of this section. For simplicity, it is assumed that the degree of combustion is 100 percent and that all carbon is oxidized to CO_2 (no CO) and all sulfur to SO_2 by the following reactions:

$$C + O_2 \rightarrow CO_2 \uparrow \qquad (1)$$

$$S + O_2 \rightarrow SO_2 \uparrow \qquad (2)$$

Other reactions in the boiler furnace are as follows:

$$H_2 + 1/2O_2 \rightarrow H_2O\ (g) \qquad (3)$$

$$H_2 + Cl_2 \rightarrow 2HCl \qquad (4)$$

Table 2.3-1. ENTHALPIES OF VARIOUS GASES

(Btu/lb of gas except as noted)

Temp., °F	CO_2	N_2	H_2O[a]	O_2	Air
100	5.8	6.4	17.8	8.8	9.6
150	17.6	20.6	40.3	19.8	21.6
200	29.3	34.8	62.7	30.9	33.6
250	40.3	47.7	85.5	42.1	45.7
300	51.3	59.8	108.2	53.4	57.8
350	63.1	73.3	131.3	64.8	70.0
400	74.9	84.9	154.3	76.2	82.1
450	87.0	97.5	177.7	87.8	94.4
500	99.1	110.1	201.0	99.5	106.7
550	111.8	122.9	224.8	111.3	119.2
600	124.5	135.6	248.7	123.2	131.6
700	150.2	161.4	297.1	147.2	156.7

[a] The enthalpies tabulated for H_2O represent a gaseous system, and enthalpies do not include the latent heat of vaporization. It is recommended that the latent heat of vaporization at 60°F (1059 Btu/lb) be used where necessary.

Table 2.3-2. MOLECULAR WEIGHTS FREQUENTLY USED IN MATERIAL BALANCE CALCULATIONS

Name	Formula	Molecular weight
Air		28.85
Calcium	Ca	40.08
Calcium carbonate (limestone)	$CaCO_3$	100.09
Calcium hydroxide	$Ca(OH)_2$	74.10
Calcium oxide (lime)	CaO	56.08
Calcium sulfate	$CaSO_4$	136.14
Calcium sulfate (dilhydrate)	$CaSO_4 \cdot 2H_2O$	172.18
Calcium sulfite	$CaSO_3$	120.14
Calcium sulfite	$CaSO_3 \cdot 1/2H_2O$	129.15
Carbon dioxide	CO_2	44.01
Hydrogen	H_2	2.02
Magnesium	Mg	24.31
Magnesium hydroxide	$Mg(OH)_2$	58.33
Magnesium oxide	MgO	40.31
Magnesium sulfate (heptahydrate)	$MgSO_4 \cdot 7H_2O$	246.51
Magnesium sulfite (hexahydrate)	$MgSO_3 \cdot 6H_2O$	212.46
Magnesium sulfite (trihydrate)	$MgSO_3 \cdot 3H_2O$	158.40
Nitrogen	N_2	28.01
Oxygen	O_2	32.00
Sulfur	S	32.06
Sulfur dioxide	SO_2	64.06
Water	H_2O	18.02

Table 2.3-3. ENERGY REQUIREMENT CALCULATIONS

C_p = Specific heat, Btu/(lb)(°F)

P = Energy required, kilowatts

E = Heat energy, Btu

H_s = Head, ft

L/G = ratio of liquor flow to flue gas rate, gal/1000 acf at the outlet

$\overset{\circ}{m}$ = air flow rate at the inlet of reheat section, lb/min

ΔP = Pressure drop through FGD system, in. H_2O

Q = Gas flow rate at the outlet of scrubber, acfm

ΔT = Degree of reheat, °F

1. Slurry recirculation pumps (70% pump efficiency assumed)

$$P = 0.000269 \times H_s \times (L/G) \times \frac{Q}{1000}$$

$$= H_s \; (L/G) \; Q \times (2.69 \times 10^{-7})$$

2. Flue gas fans

$$P = 0.0002617 \times \Delta P \times Q \quad \text{(assuming 80\% efficiency)}$$

3. Reheat of scrubber flue gas

$$E = 0.01757 \; \overset{\circ}{m} \; C_p \; \Delta T$$

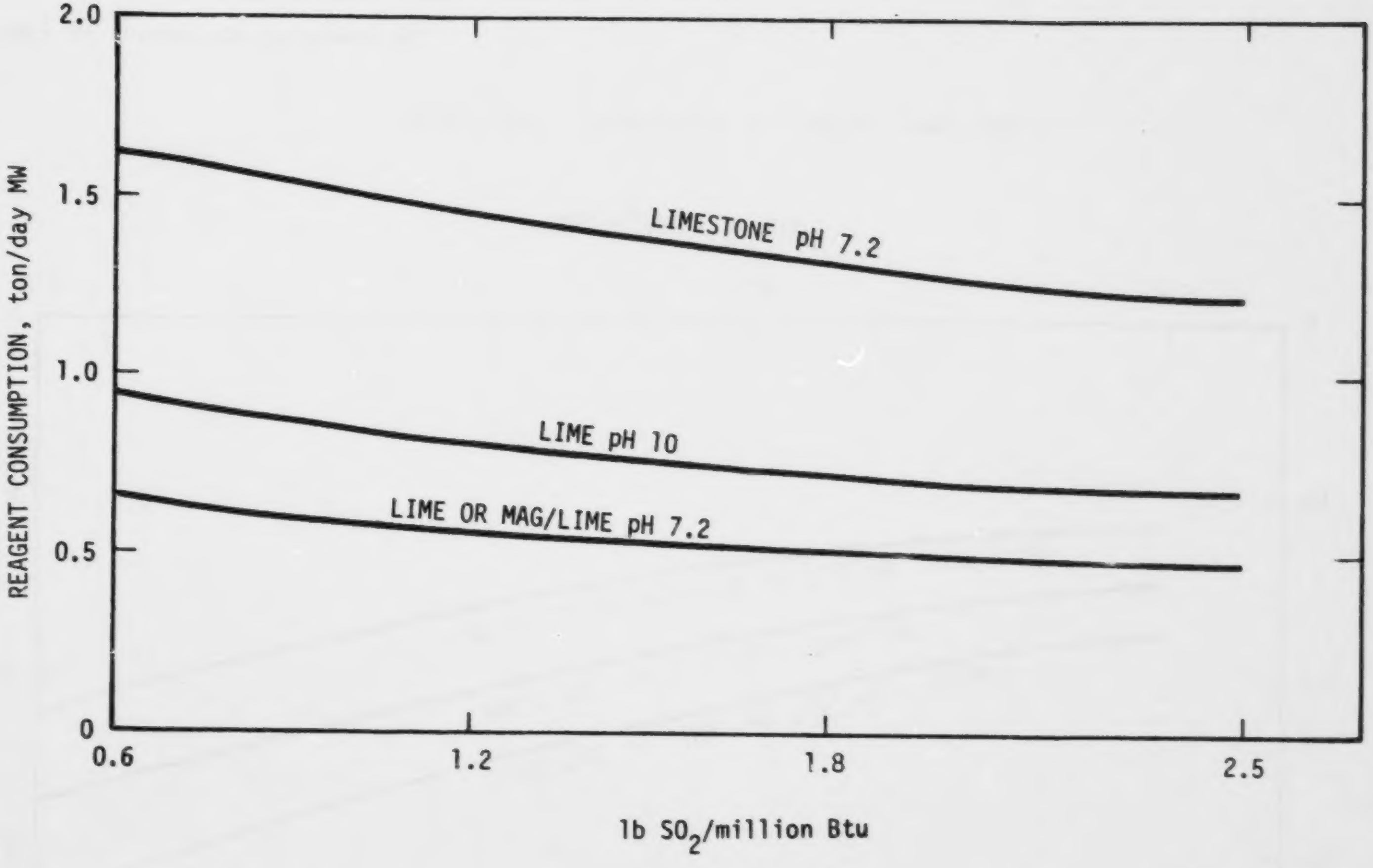


Figure 2.3-1. Additive vs. outlet requirements.

Courtesy of Combustion Engineering.

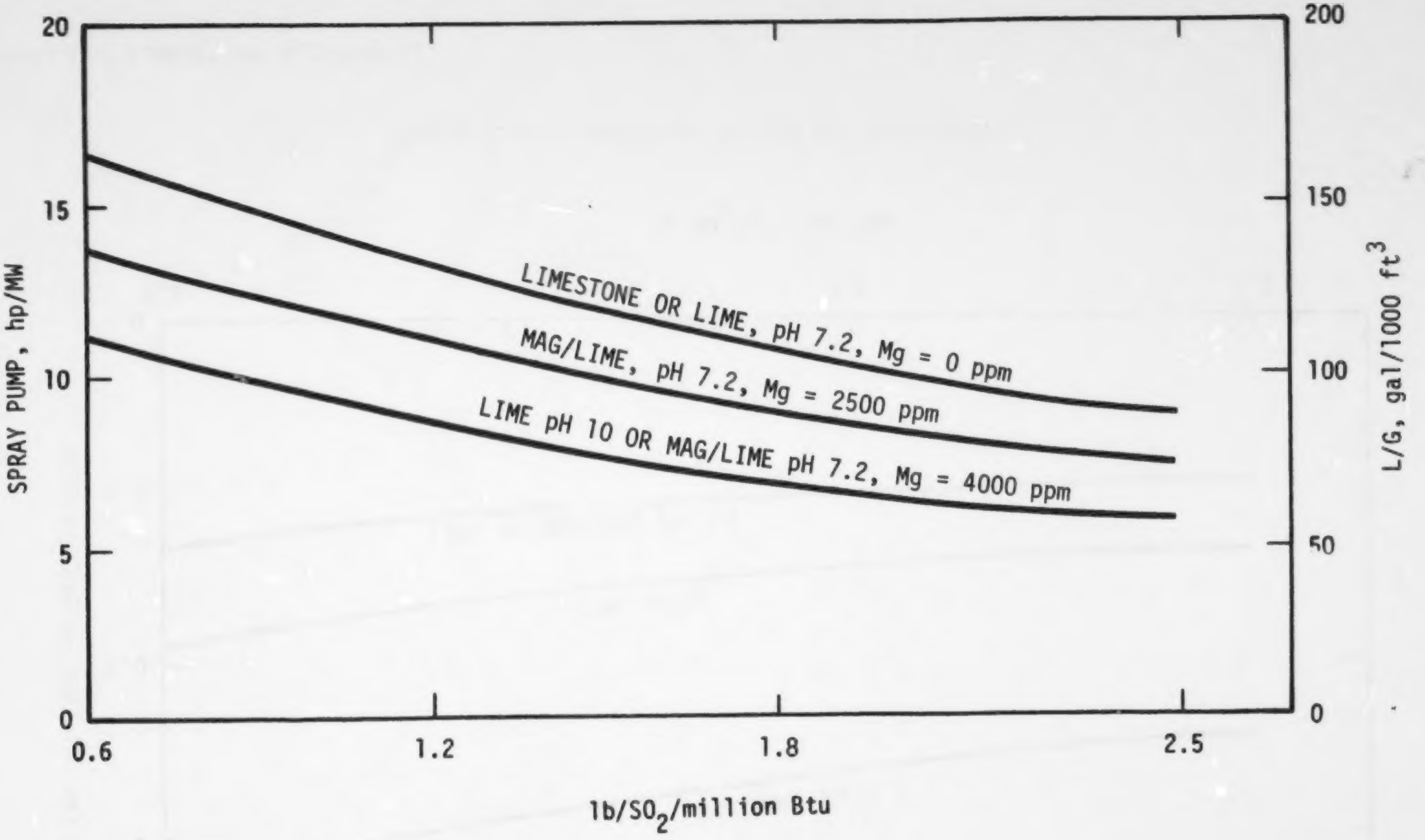


Figure 2.3-2. Horsepower vs. outlet requirements

Courtesy of Combustion Engineering.

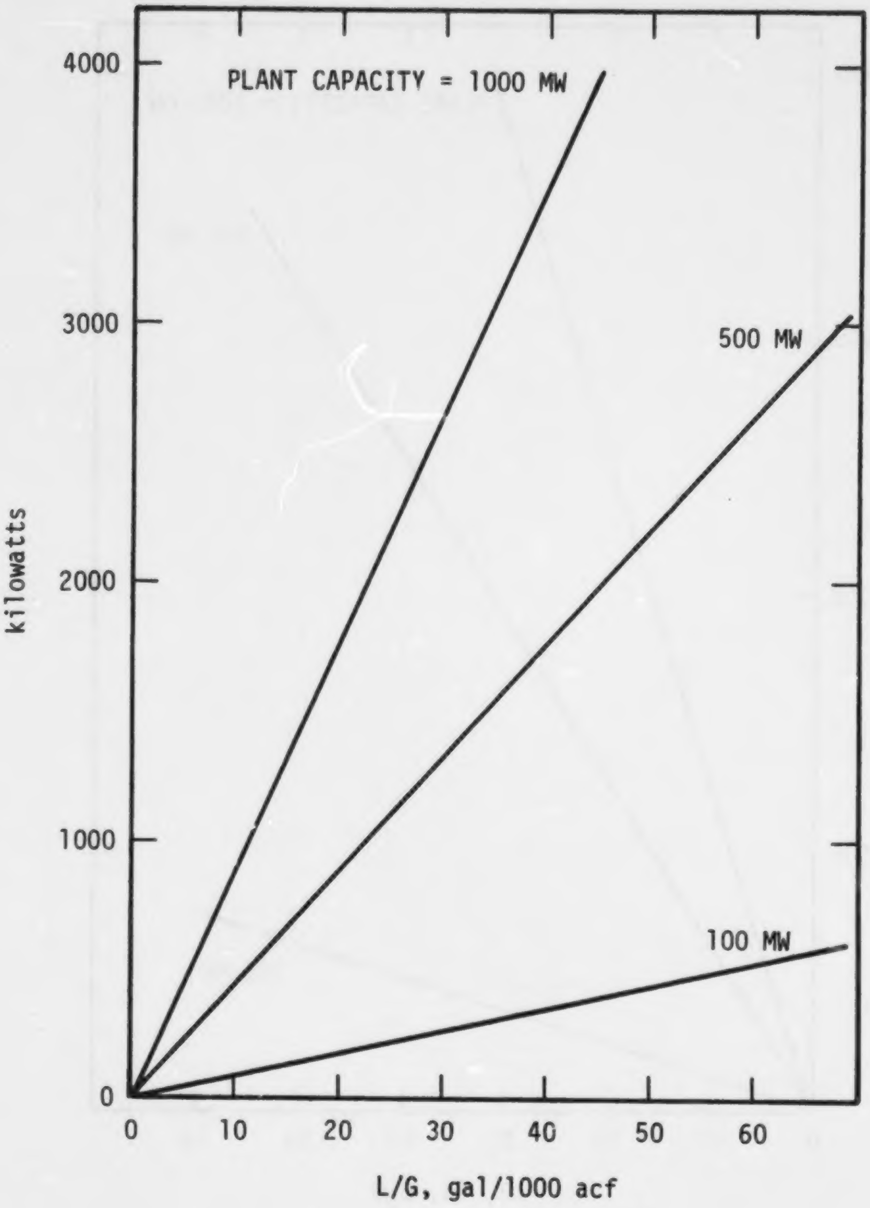


Figure 2.3-3. Recirculation pump energy requirement.

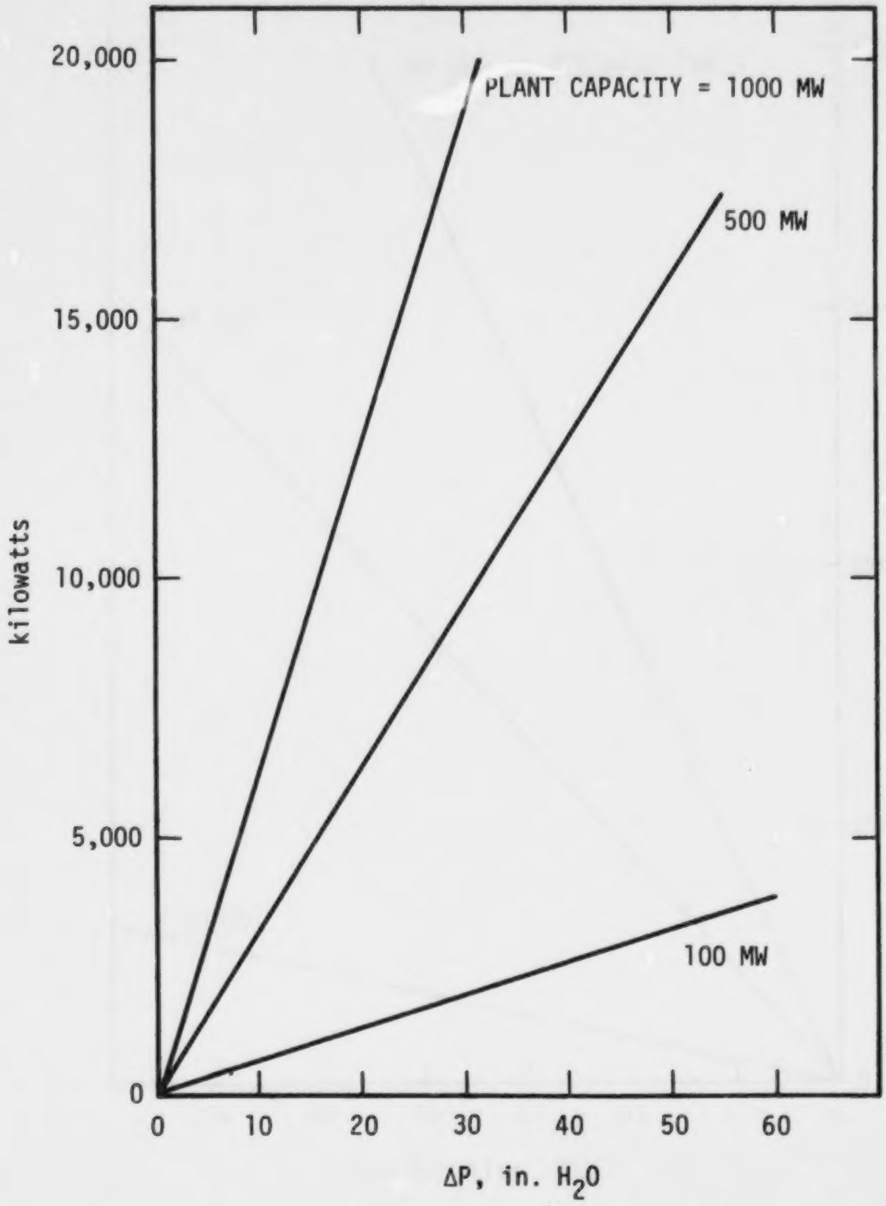


Figure 2.3-4. Fan energy requirement.

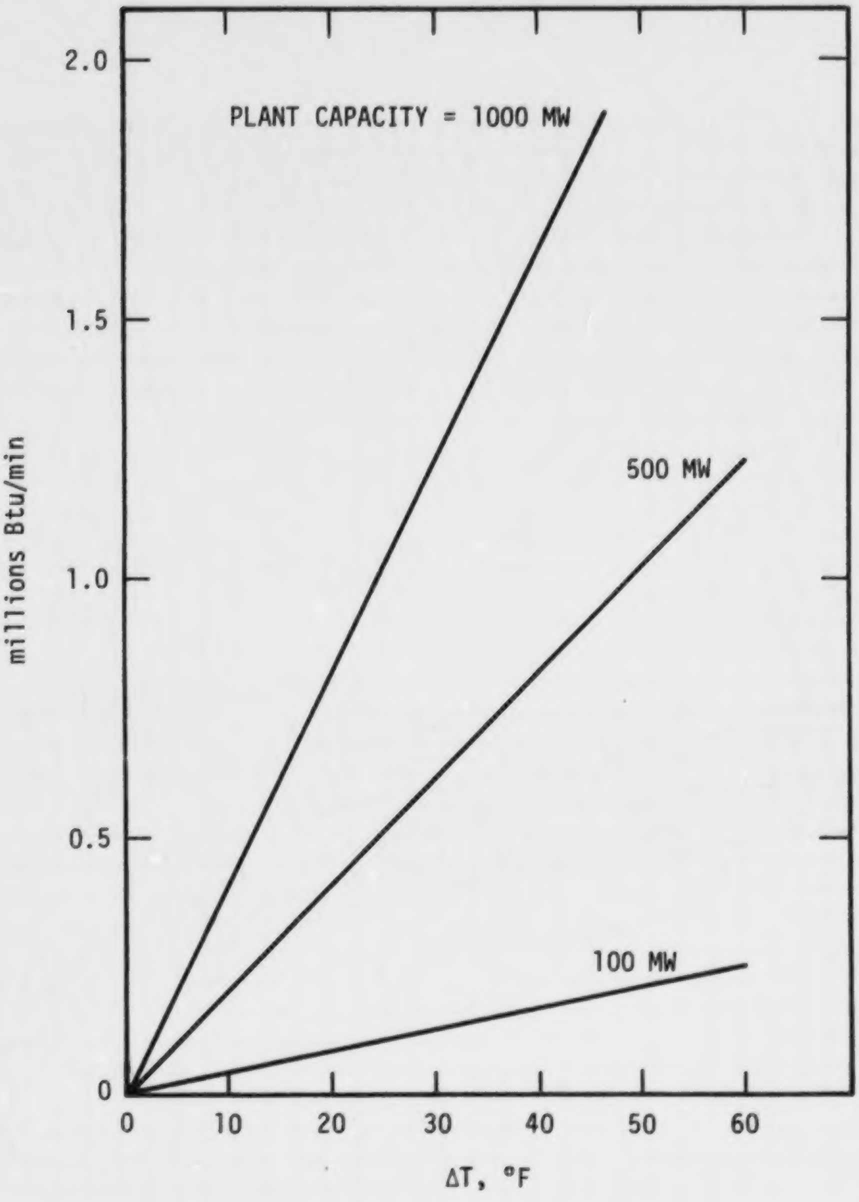


Figure 2.3-5. Reheat energy requirement.

Note: Flue gas volume at reheat is assumed to be 21,000 acf/MW.

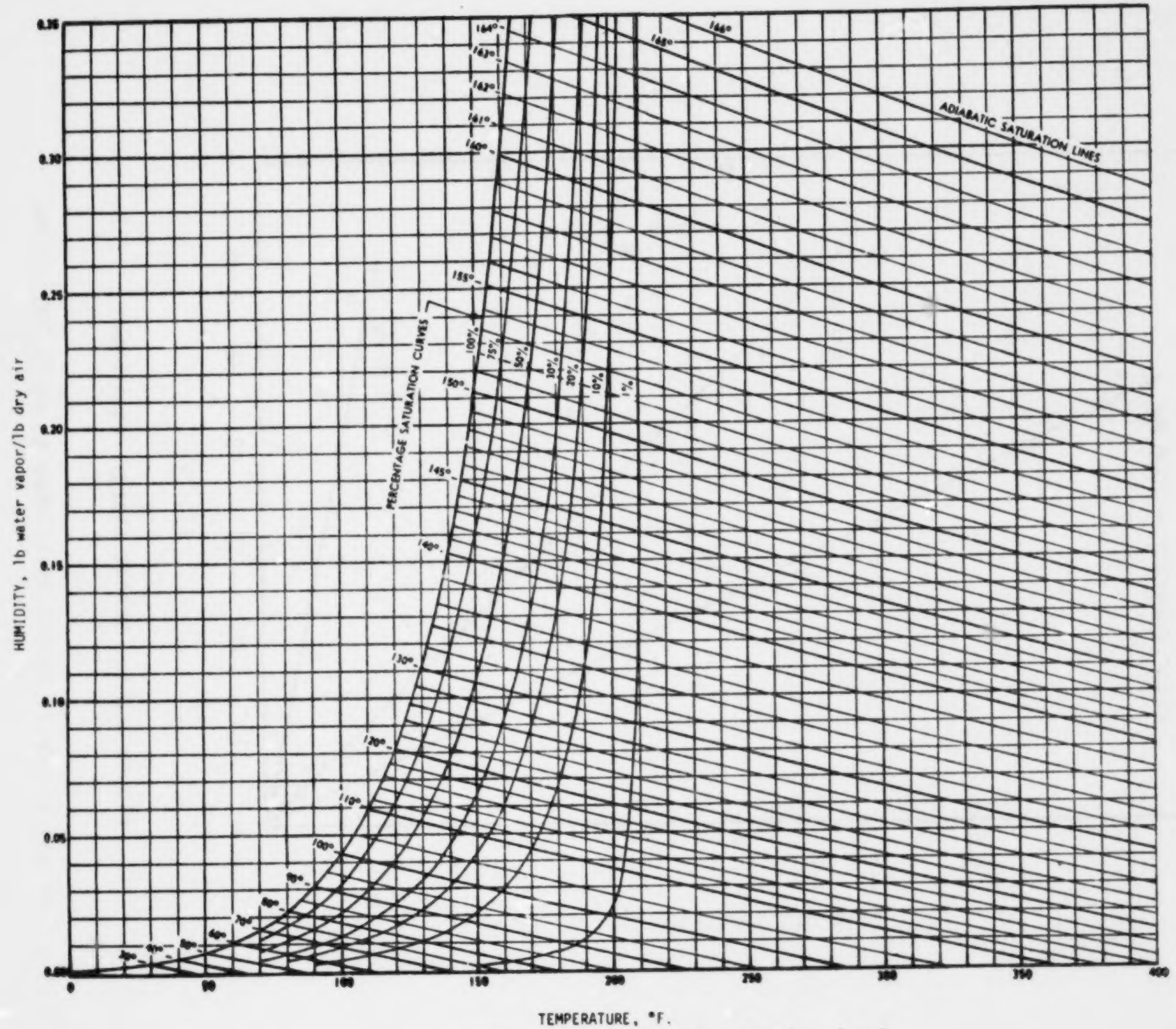


Figure 2.3-6. Psychrometric chart.

Temperature Range: 0° to 400°F; Pressure, 1 atm.

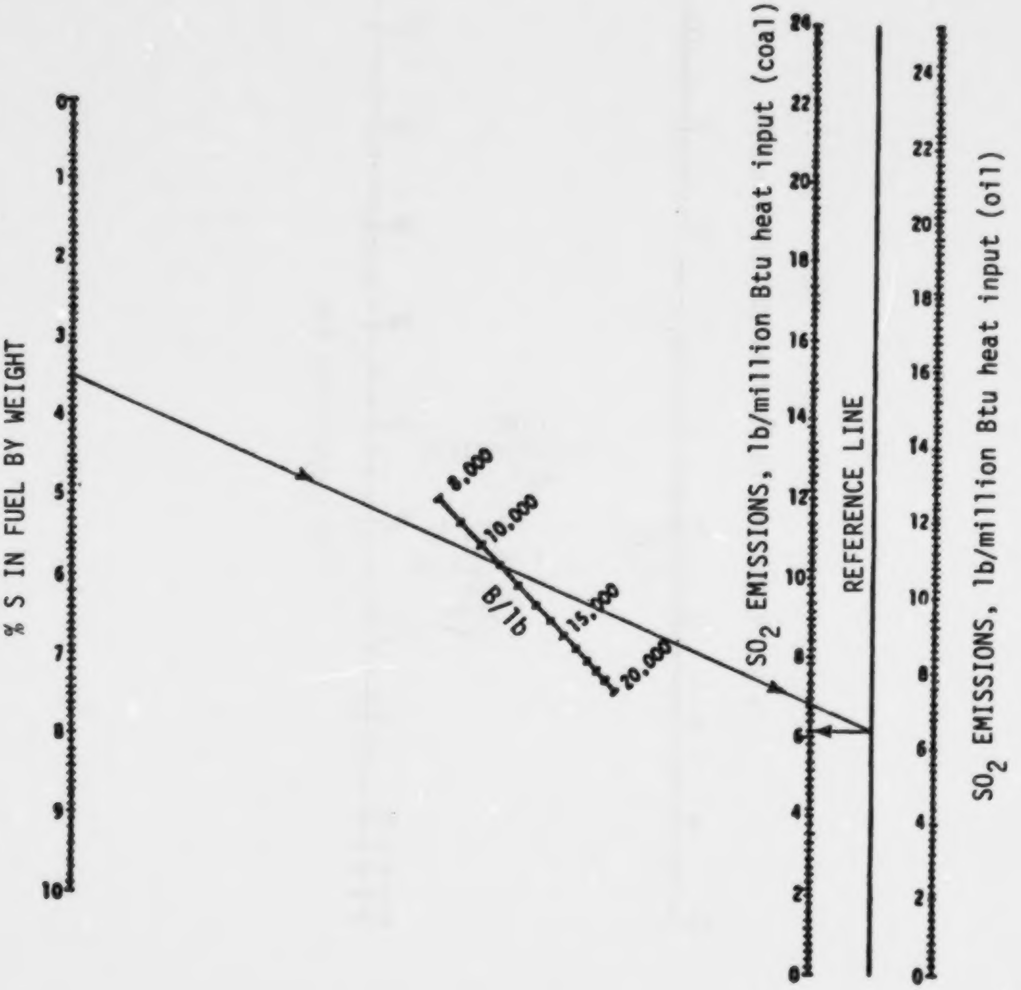


Figure 2.3-7. SO$_2$ emission calculation.

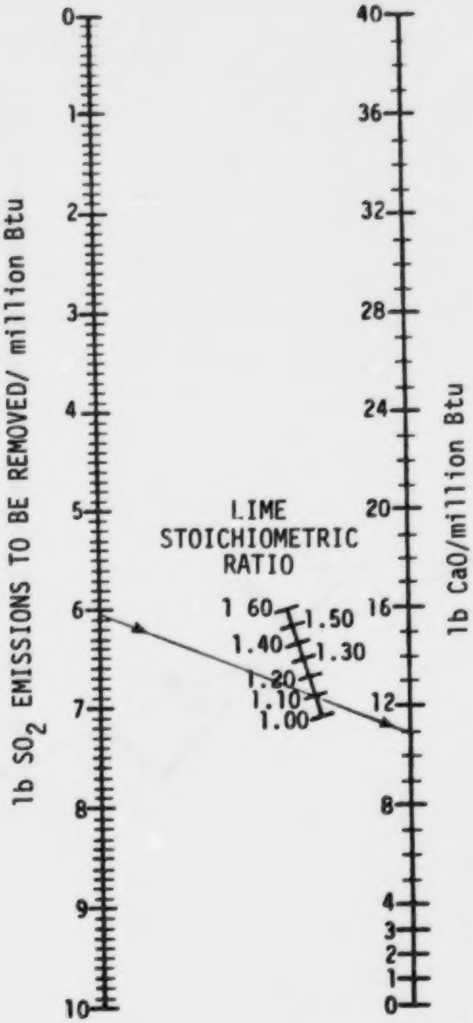


Figure 2.3-8. Lime requirement calculation.

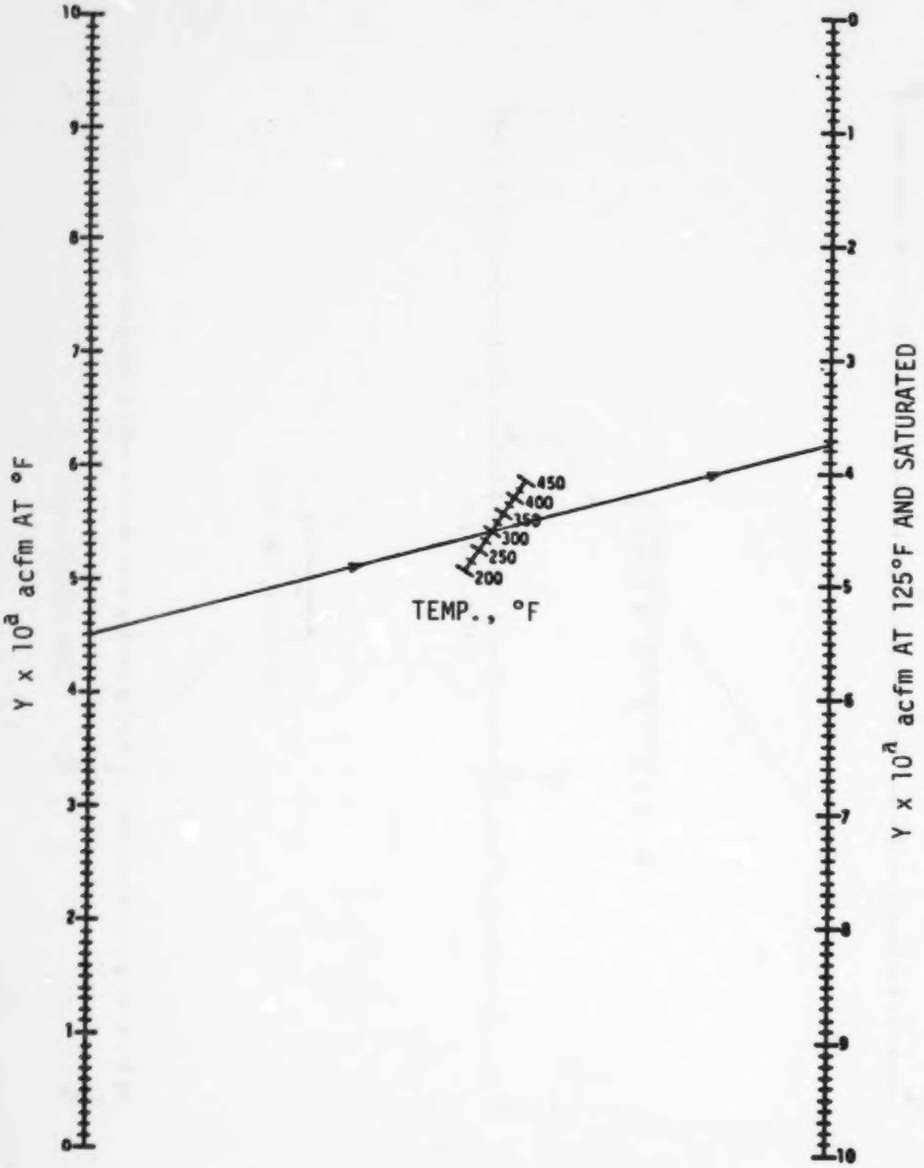


Figure 2.3-9. **Saturated gas calculation.**

Note: The superscript "a" may be 10^3, 10^6, etc., but, it is the same on both the left and right ordinates for each case.

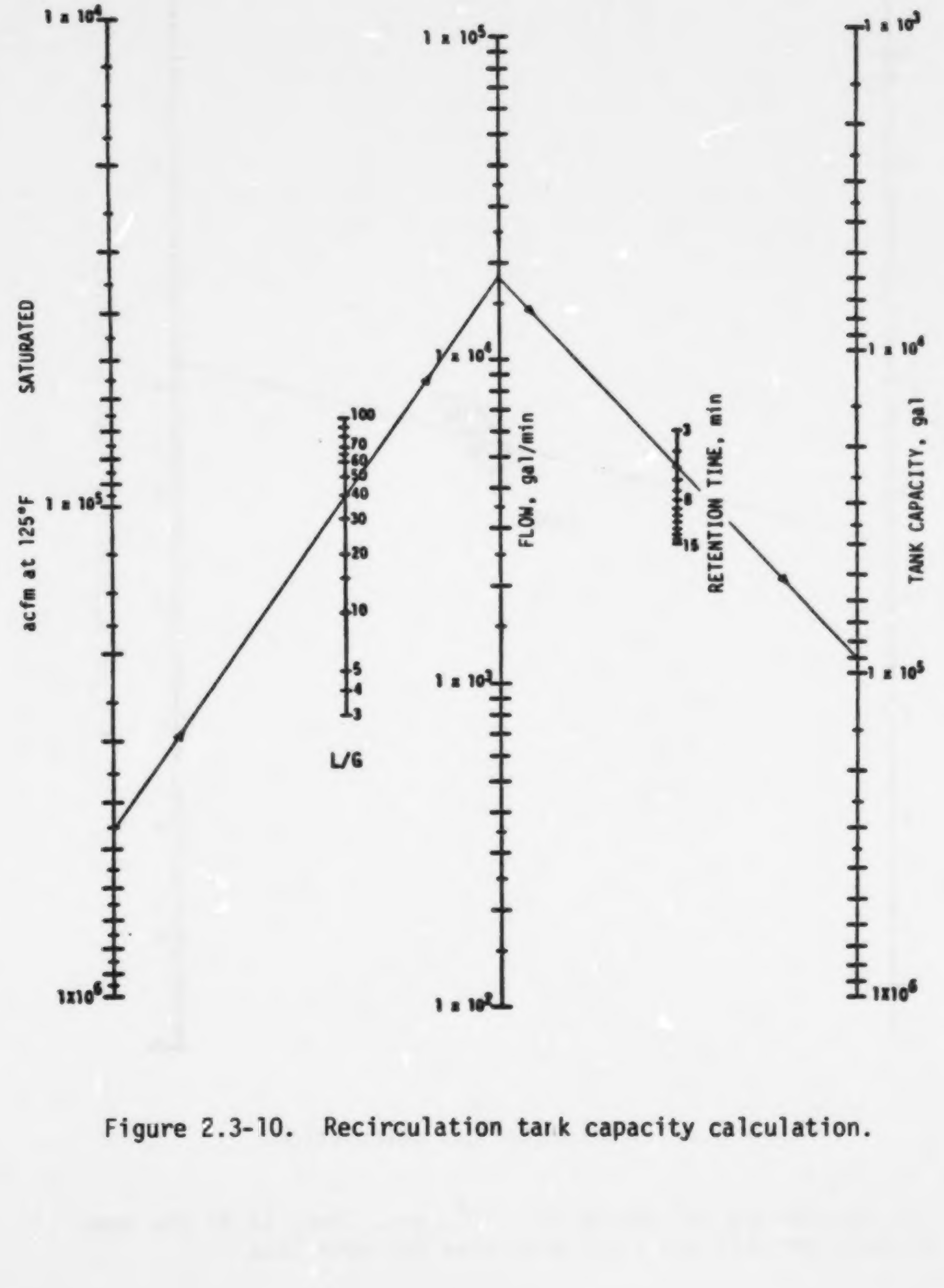


Figure 2.3-10. Recirculation tank capacity calculation.

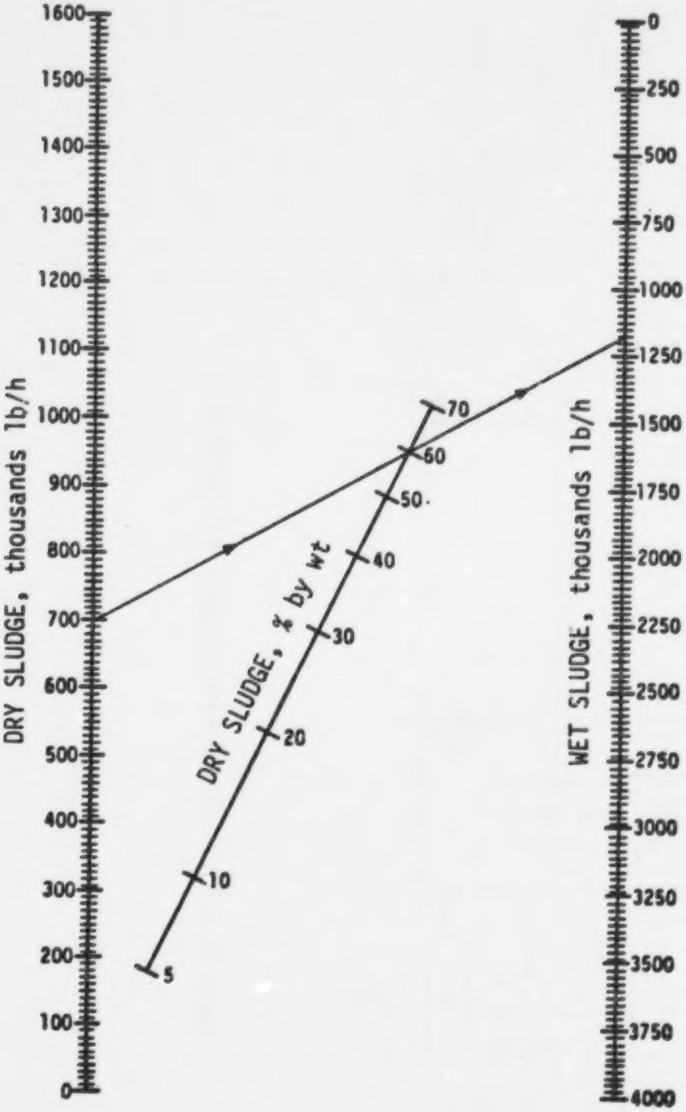
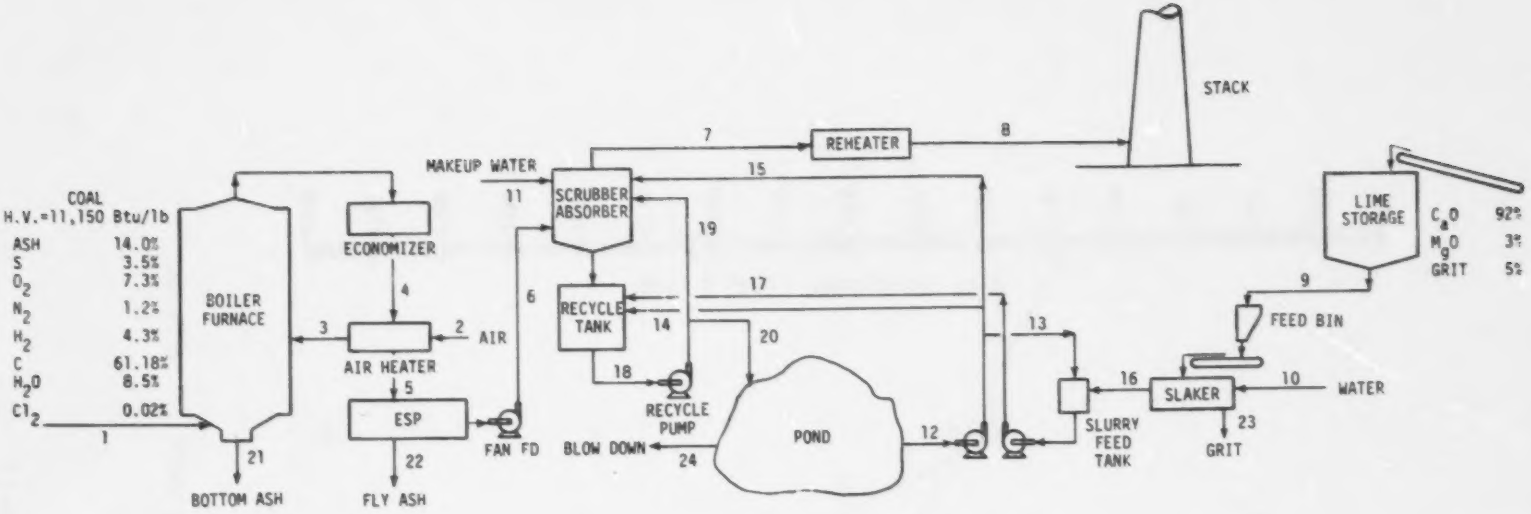


Figure 2.3-11. Wet sludge calculation.



COAL
H.V.=11,150 Btu/lb
ASH 14.0%
S 3.5%
O_2 7.3%
N_2 1.2%
H_2 4.3%
C 61.18%
H_2O 8.5%
Cl_2 0.02%
1
BOILER FURNACE
21
BOTTOM ASH
ECONOMIZER
4
3
AIR HEATER
2
AIR
5
ESP
22
FLY ASH
FAN FD
6
MAKEUP WATER
11
SCRUBBER ABSORBER
7
REHEATER
8
STACK
15
19
RECYCLE TANK
17
14
20
18
RECYCLE PUMP
BLOW DOWN
24
POND
12
13
SLURRY FEED TANK
16
SLAKER
10
WATER
23
GRIT
FEED BIN
9
LIME STORAGE
C_aO 92%
M_gO 3%
GRIT 5%

Figure 2.3-12. 500-MW model plant for Example 1.

Table 2.3-4. DESIGN INFORMATION

Plant capacity		500 MW
Coal:	Consumption	420,000 lb/h
	High heating value	11,150 Btu/lb
	Sulfur content	3.5%
	Oxygen content	7.3%
	Hydrogen content	4.3%
	Nitrogen content	1.2%
	Carbon content	61.18%
	Chloride content	0.02%
	Moisture content	8.5%
	Ash content	14.0%
	bottom ash/fly ash	20 lb/80 lb
Excess air: (70°F, 80% relative humidity)	To air heater	40%
	To boiler-furnace	20%
Lime:	Utilization	91%
	Stoichiometric ratio	1.10
Scrubber:	L/G ratio	40 gal/1000 acf
	Inlet gas temperature	285°F
Sulfite-to-sulfate oxidation		20%
Reheating		40°F
Maximum emission: (NSPS)	Particulate	0.1 lb/million Btu
	SO_2	1.2 lb/million Btu
Solids:	Slaker	35%
	Slurry feed tank	20%
	Recycle tank	14%

In these reactions, some of the hydrogen in the coal is consumed to form hydrochloric acid. At steady state, this acid is completely absorbed in the scrubbing solution and removed with interstitial water in the waste sludge.

In some coals, calcium in the ash reacts with sulfur dioxide or sulfur trioxide; this effect is neglected here.

Air at 70°F and 80 percent relative humidity (annual average) is supplied to the boiler furnace through an air heater. The excess amounts of air supplied to the furnace (Stream 3) and to the air heater (Stream 2) are 20 percent and 40 percent of the theoretical air requirement for coal combustion, respectively. Twenty percent excess air from Stream 2 is assumed to leak to Stream 5 at the air heater.

The fly ash in gas Stream 5 is primarily removed in an ESP, and some fly ash removal occurs in the scrubber section. The maximum particulate emission must be in compliance with the NSPS promulgated by EPA in December 1971, which is 0.1 lb/million Btu heat input. The resulting gas (Stream 6) enters the SO_2 absorber at 285°F, and the SO_2 is removed by a countercurrent lime scrubbing process. The current NSPS limitation for SO_2 is 1.2 lb/million Btu heat input.

The temperature of the saturated flue gas from the absorber (Stream 7) is increased 40°F in a reheater. It is assumed that there is no mist carryover in the gas. The cleaned and reheated flue gas (Stream 8) is discharged to the atmosphere through a stack. In calculating gas flow rate the ideal gas laws are assumed.

Typical pressure drop data are presented in Table 2.3-5.

Table 2.3-5. TYPICAL PRESSURE DROP DATA

Equipment	Pressure drop, in. H_2O
SO_2 absorber	
(mobile bed)	10-12
(spray tower)	5-6
Demister	2
Reheater	3
Duct work	3

A 35 percent lime slurry is prepared in a slaker using fresh water and lime. A typical lime analysis is presented in Table 2.3-6. Sixty percent of the inert materials is removed while the slurry is in the slaker. In this example, lime is used in 10 percent excess of that required by the stoichiometry.

Table 2.3-6. LIME ANALYSIS
(wt. percent)

CaO	92
MgO	3
Inert	5
Total	100

In the slaker, the hydration reactions of lime containing MgO as an impurity are expressed by the following:

$$CaO + H_2O \rightarrow Ca(OH)_2$$

$$MgO + H_2O \rightarrow Mg(OH)_2$$

This 35 percent slurry (specific gravity = 1.24) is then diluted to 20 percent (specific gravity = 1.12) with a portion of recovered water (Stream 13) in a slurry feed tank, then pumped to a recycle tank, which maintains 14 percent solids concentration (specific gravity = 1.09).

Slurry from the recycle tank is recirculated through the absorber for removal of SO_2, and a portion of the slurry (to be determined by the material balance) is purged to a pond for disposal (Stream 20).

The liquid-to-gas (L/G) ratio in the absorber normally ranges from 40 to 60 gal of slurry per 1000 acf of gas, depending on the sulfur content, and the absorber type and efficiency. In this example, the L/G is 40. The spent slurry from the absorber returns to the recycle tank together with wash water from the mist eliminator (Stream 11) and the recycled wash water (Stream 15). The flow rate in the mist eliminator wash (Stream 15) is 300 gal/min or 150,000 lb/h. The recycled liquor from the pond is added to the recycle tank.

In the scrubber, both calcium and magnesium ions react with SO_2. The SO_2 reacts with dissolved alkalines such as Mg^{++} more rapidly than with suspended alkaline solids such as $Ca(OH)_2$. This follows the reaction:

$$2SO_2 + 2H_2O + Mg^{++} \rightarrow [Mg^{++} + 2HSO_3^-](\text{dissolved solids}) + 2H^+ \tag{5}$$

Some of the $Mg(OH)_2$ (assuming 5 percent in this example) forms $MgCO_3$ by the reaction with CO_2 in the flue gas:

$$Mg(OH)_2 + CO_2 \rightarrow MgCO_3(s) + H_2O \tag{6}$$

The calcium ions tend to regenerate the bisulfite ions in the same manner as in double alkali FGD systems. Calcium hydroxide, $Ca(OH)_2$, reacts with magnesium bisulfite, $Mg(HSO_3)_2$ to regenerate the magnesium sulfite $Mg(SO_3)$, and form calcium sulfite, $CaSO_3$. At steady state, $MgSO_3$ (dissolved solids) as well as $CaCl_2$ is removed from the system with the interstitial water in the waste sludge. Most of the SO_2 is ultimately removed by reaction with $Ca(OH)_2$. The overall reaction is:

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 \cdot 1/2H_2O + 1/2\ H_2O) \tag{7}$$

Some of the calcium sulfite formed in Reaction (7) is oxidized to sulfate with the oxygen in the flue gas. The degree of oxidation in this example is 20 percent. The overall reaction is expressed by:

$$Ca(OH)_2 + SO_2 + 1/2O_2 + H_2O \rightarrow CaSO_4 \cdot 2H_2O \tag{8}$$

The excess hydrated lime, $Ca(OH)_2$, reacts with CO_2 in the flue gas and is discharged to the pond as calcium carbonate ($CaCO_3$) according to the reaction:

$$Ca(OH)_2\ (\text{excess}) + CO_2(g) \rightarrow CaCO_3 \downarrow + H_2O \tag{9}$$

Therefore, the solids in the waste (Stream 20) are $CaSO_3 \cdot 1/2\ H_2O$, ash, $CaCO_3$, grit, and crystals of $CaSO_3 \cdot 1/2H_2O$ and $CaSO_4 \cdot 2H_2O$. The amount of dissolved gas in the waste stream is neglected.

A slipstream of recycle slurry is sent to the pond (Stream 20); 50 percent suspended solids settles in the pond. The water is recovered in Stream 12 and and reused in Streams 13, 14, and 15. The makeup water, which includes pump seal water and equipment wash water, is supplied through Stream 11.

The design information discussed in the section is summarized in Table 2.3-4.

2.3.3 Sample Calculations

The overall material balance includes the boiler furnace system and the FGD system, as shown in Figure 2.3-13. Inputs to the combined systems consist of coal, air, lime, and water. Outputs from these systems consist of ash (bottom and a portion of fly ash), waste sludge, and cleaned flue gas. Only the amount of coal consumption is known, however, and the rest of the information must be calculated from a material balance for each major component of the overall system. These material balance calculations are performed in five steps, as follows:

- The boiler-furnace (Step 1)
- SO_2 and particulate removal (Step 2)
- Slurry preparation/lime requirement (Step 3)
- Scrubber system (Step 4)
- Overall water balance (Step 5)

The material balance of a boiler-furnace (Step 1) is represented in Figure 2.3-14 and the elements are summarized below.

Input:
1. Weight of coal charged
2. Weight of dry air supplied
3. Weight of moisture in air and coal supplied

Output:
1. Weight of dry gaseous products
2. Weight of water vapor in gaseous products
3. Weight of refuse (bottom and fly ash)*

Coal is charged at 420,000 lb/h. The rest of the items, however, must be calculated from the design information (Table 2.3-4) and the coal combustion properties discussed in Section 2.3.2. This calculation requires a component material balance.

The minimum amounts of fly ash and SO_2 (Step 2) to be removed are determined by the current NSPS limitation. Eighty percent of overall particulate (fly ash)* removal is achieved in an ESP, and 20 percent in the SO_2 scrubber. From the input-output data, the minimum acceptable efficiencies of the ESP and the SO_2 scrubber can be calculated. The material balance of this step involves only SO_2 and particulate, and the irrelevant inputs to the FGD system are eliminated from Figure 2.3-15 for simplicity.

---

* Since no mist carryover is assumed, fly ash and particulate are essentially the same.

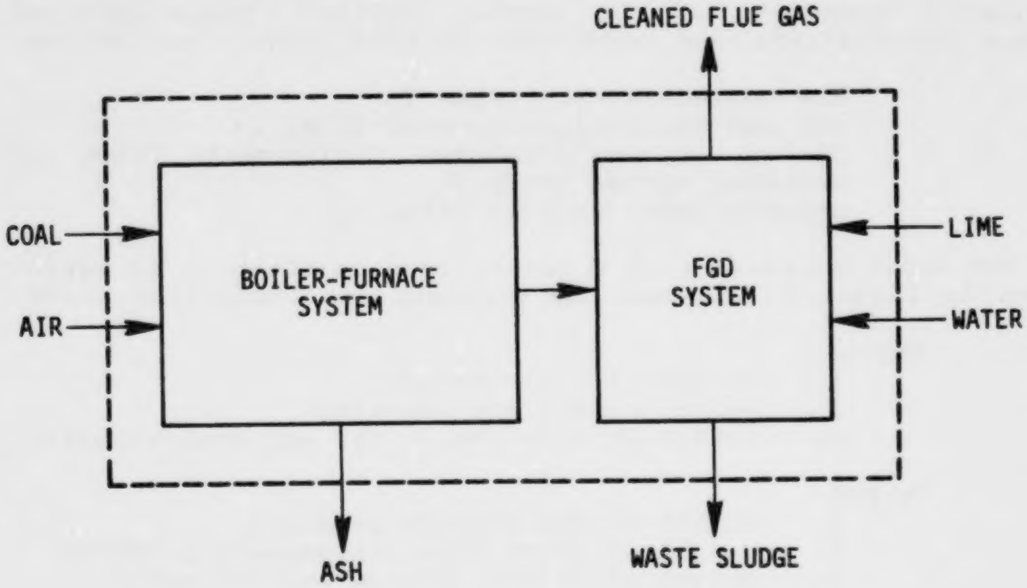

CLEANED FLUE GAS
COAL
AIR
BOILER-FURNACE SYSTEM
FGD SYSTEM
LIME
WATER
ASH
WASTE SLUDGE

Figure 2.3-13. Overall material balance.

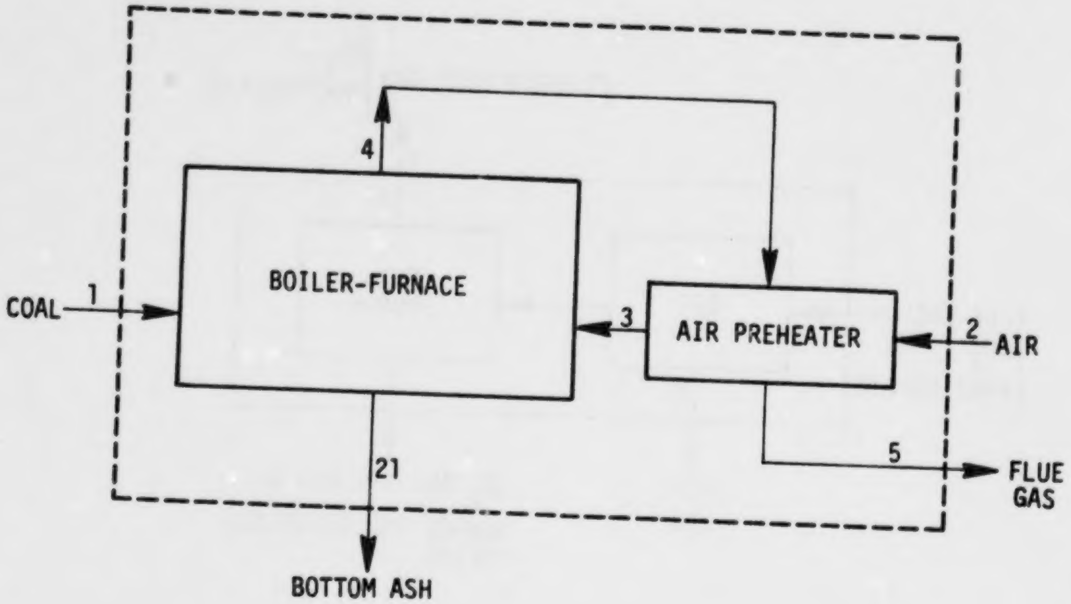

BOILER-FURNACE
AIR PREHEATER
COAL
1
2
AIR
3
4
5
FLUE GAS
21
BOTTOM ASH

Figure 2.3-14. Boiler-furnace material balance.

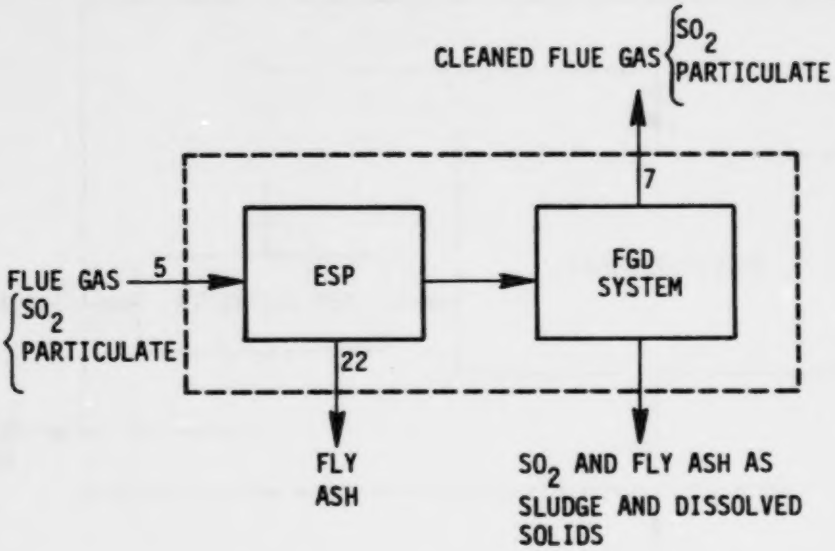

CLEANED FLUE GAS
SO2
PARTICULATE
7
FLUE GAS
5
SO2
PARTICULATE
ESP
FGD SYSTEM
22
FLY ASH
SO2 AND FLY ASH AS SLUDGE AND DISSOLVED SOLIDS

Figure 2.3-15. SO_2 and particulate balance.

The theoretical lime requirement (Step 3) depends on the amount of SO_2 to be removed from the FGD system, since removal of one mole SO_2 requires one mole of alkalinity (eigher CaO or MgO). The actual supply of lime will be 110 percent of the theoretical lime requirement (1.1 stoichiometric ratio), as discussed in Section 2.3.2. Water required for slurry preparation can be calculated in this step.

Step 4 gives an overall material balance of the scrubber system, as shown in Figure 2.3-16. Each component of waste sludge is calculated with the process chemistry described in Section 2.3.2. At steady state, the dissolved solids and the chloride are analyzed based on the assumption that these species are removed with the interstitial water in the waste sludge. This determines the maximum concentrations of these species in the scrubbing system.

The temperature of the flue gas leaving the scrubber is determined by assuming adiabatic saturation. Use of a psychrometric chart for this purpose will be discussed. The final conditions of the cleaned flue gas leaving the FGD system and the makeup water requirement to this scrubber system are calculated in this step. The overall water balance is determined in the next step.

Step 5, the overall water balance, includes the waste treatment system, the distribution of recovered water, and the water inputs and outputs to the combined system.

Following the calculation of each of these steps is a summary in table or flow chart form. Stream numbers indicated in the calculations are from Figure 2.3-12.

2.3.4 Boiler Furnace Material Balance (Step 1)

This step calculates the input and output data for coal combustion in the boiler-furnace, as shown in Figure 2.3-17. All calculations are based on 420,000 lb of coal charged per hour. The figures in the coal analysis are significant to 0.01 percent, which corresponds to 42 lb/h. For hydrogen, this represents about 40 mol/h; for chlorine and sulfur, about 1 mol/h. In this example, therefore, results are calculated to the nearest 10 lb/h and the nearest 0.1 mol/h.

2.3.4.1 Ash Balance--

This is a straightforward calculation from the ash content of coal and the coal charged:

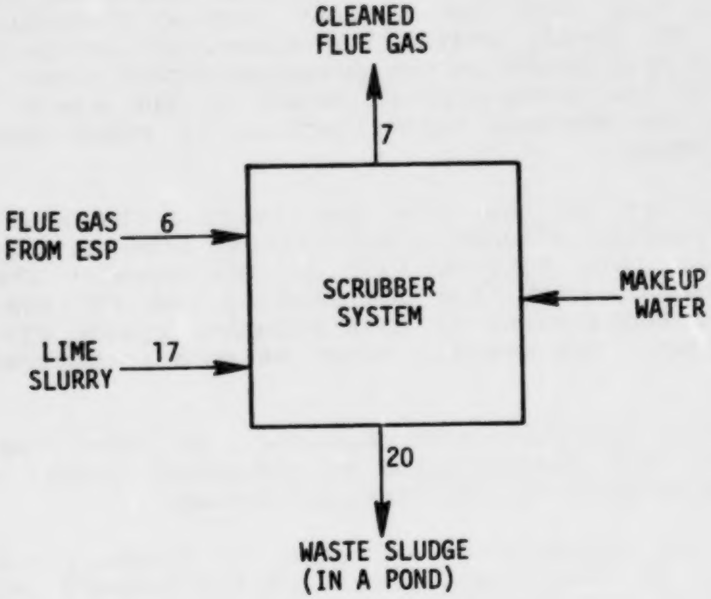
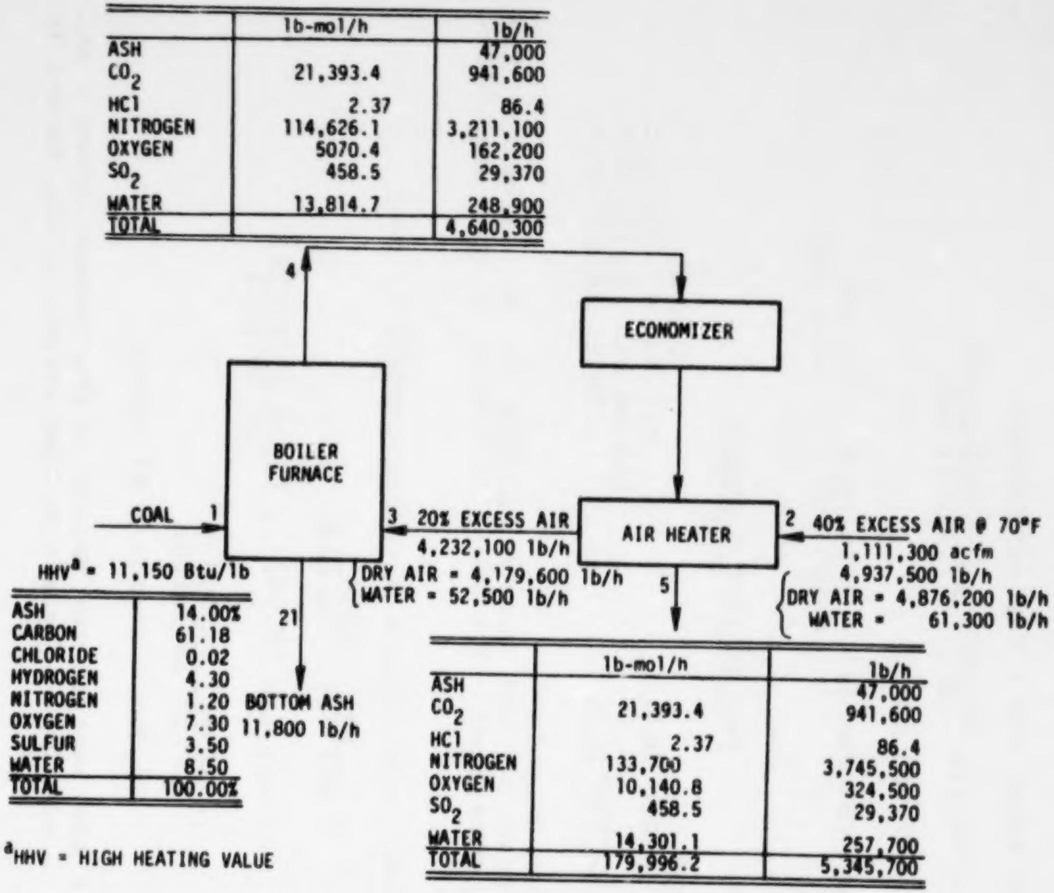

CLEANED FLUE GAS
7
FLUE GAS FROM ESP
6
LIME SLURRY
17
SCRUBBER SYSTEM
MAKEUP WATER
20
WASTE SLUDGE (IN A POND)

Figure 2.3-16. Scrubber material balance.


BOILER FURNACE
ECONOMIZER
AIR HEATER
COAL
1
2
3
4
5
21
20% EXCESS AIR
4,232,100 lb/h
DRY AIR = 4,179,600 lb/h
WATER = 52,500 lb/h
40% EXCESS AIR @ 70°F
1,111,300 acfm
4,937,500 lb/h
DRY AIR = 4,876,200 lb/h
WATER = 61,300 lb/h
BOTTOM ASH
11,800 lb/h

HHV[a] = 11,150 Btu/lb

ASH	14.00%
CARBON	61.18
CHLORIDE	0.02
HYDROGEN	4.30
NITROGEN	1.20
OXYGEN	7.30
SULFUR	3.50
WATER	8.50
TOTAL	100.00%

[a] HHV = HIGH HEATING VALUE

	lb-mol/h	lb/h
ASH		47,000
CO_2	21,393.4	941,600
HCl	2.37	86.4
NITROGEN	114,626.1	3,211,100
OXYGEN	5070.4	162,200
SO_2	458.5	29,370
WATER	13,814.7	248,900
TOTAL		4,640,300

	lb-mol/h	lb/h
ASH		47,000
CO_2	21,393.4	941,600
HCl	2.37	86.4
NITROGEN	133,700	3,745,500
OXYGEN	10,140.8	324,500
SO_2	458.5	29,370
WATER	14,301.1	257,700
TOTAL	179,996.2	5,345,700

Figure 2.3-17. Detailed boiler-furnace material balance.

$$\text{Total ash} = \text{coal charged} \times \text{ash content of coal}$$

$$= 420{,}000\ \frac{\text{lb coal}}{\text{h}} \times \frac{\text{14 lb ash}}{\text{100 lb coal}}$$

$$= 58{,}000\ \text{lb/h},$$

which consists of 80 percent fly ash and 20 percent bottom ash. Thus,

$$\text{Fly ash} = \text{total ash} \times \text{fly ash content}$$

$$= 58{,}800\ \frac{\text{lb ash}}{\text{h}} \times \frac{\text{80 lb fly ash}}{\text{100 lb ash}}$$

$$= 47{,}000\ \text{lb/h},$$

$$\begin{aligned}\text{Bottom ash (Stream 21)} &= \text{total ash} - \text{fly ash}\\ &= (58{,}800 - 47{,}000)\ \text{lb/h}\\ &= 11{,}800\ \text{lb/h}.\end{aligned}$$

Ash Balance Summary

Input		Output	
In coal	58,800 lb/h	Fly ash	47,000 lb/h
		Bottom ash	11,800 lb/h
Total	58,800 lb/h	Total	58,800 lb/h

2.3.4.2 Carbon Balance--

The purpose of the carbon balance is to calculate the amount of CO_2 generated. The moles of carbon in coal are calculated as:

$$\text{Mol carbon} = \text{coal charge} \times \text{carbon content of coal}$$

$$\times \frac{\text{mol carbon}}{\text{mol. wt.* in coal}}$$

$$= 420{,}000\ \frac{\text{lb coal}}{\text{h}} \times \frac{\text{61.18 lb carbon}}{\text{100 lb coal}}$$

$$\times \frac{\text{lb-mol carbon}}{\text{12.011 lb carbon}}$$

$$= 21{,}393.4\ \text{lb-mol/h of carbon}$$

This value is the same as the amount of CO_2 formed, since 1 mol carbon forms 1 mol CO_2. Therefore, the weight of CO_2 formed is

---

* mol. wt. = molecular weight

$$\text{Weight of } CO_2 = \frac{\text{lb-mol } CO_2}{h} \times \frac{\text{mol. wt. of } CO_2}{\text{mol } CO_2}$$

$$= 21{,}393.4\ \frac{\text{lb-mol } CO_2}{h} \times \frac{44.009\ \text{lb } CO_2}{\text{lb-mol } CO_2}$$

$$= 941{,}600\ \text{lb } CO_2/h$$

2.3.4.3 Chloride Balance--

Chloride in coal combines with hydrogen by Reaction (4) [$H_2 + Cl_2 \rightarrow 2HCl$]. The amount of HCl formed is calculated thus:

$$\text{Amount of HCl} = \text{coal charged} \times \text{chloride content of coal, as } Cl_2$$

$$\times \frac{2 \text{ mol HCl}}{\text{mol. wt. of chloride } (Cl_2)}$$

$$= 420{,}000\ \frac{\text{lb coal}}{h} \times \frac{0.02\ \text{lb } Cl_2}{100\ \text{lb coal}} \times \frac{2\ \text{lb-mol HCl}}{2 \times 35.452\ \text{lb } Cl_2}$$

$$= 2.4\ \text{lb-mol HCl}/h$$

$$\text{or} \times \frac{36.461\ \text{lb HCl}}{\text{lb-mol HCl}} = 90.0\ \text{lb HCl}/h$$

2.3.4.4 Theoretical Amount of Air Required for Combustion--

The weight of air theoretically required for complete combustion depends on the chemical composition of the fuel and the stoichiometric relations involved in combustion. Since the one element in common for all combustion reactions is oxygen, the mass flow rate of air required for combustion must be calculated from an oxygen balance. The oxygen already in the coal is assumed to be used in the combustion process.

Calculating the oxygen requirements for combustible constituents of coal entails the requirement for carbon and sulfur. Carbon in coal was calculated at 21,393.4 lb-mol/h carbon. Since 1 mol oxygen is required per mol carbon by Reaction (1) [$C + O_2 \rightarrow CO_2$], oxygen required is 21,393.4 lb-mol/h.

The moles of sulfur present in the coal at this feed rate are calculated as follows:

$$\text{Mol sulfur} = \text{coal charged} \times \text{sulfur content of coal} \times \frac{\text{mol sulfur}}{\text{mol. wt. of sulfur}}$$

$$= 420{,}000\ \frac{\text{lb coal}}{h} \times \frac{3.5\ \text{lb sulfur}}{100\ \text{lb coal}} \times \frac{\text{lb-mol sulfur}}{32.06\ \text{lb sulfur}}$$

$$= 458.5\ \text{lb-mol sulfur}/h$$

Since 1 mol oxygen is required per mol sulfur ($S + O_2 \rightarrow SO_2$), the oxygen required is also 458.5 lb-mol/h.

Some of the hydrogen in coal forms hydrochloric acid by Reaction (4), and the available hydrogen in coal for Reaction (3) is

$$
\begin{aligned}
\text{Mol hydrogen} &= \text{coal charged x } (H_2 \text{ content} - Cl_2 \text{ content}) \\
&\quad \text{x } \frac{\text{mol hydrogen}}{\text{mol. wt. of hydrogen}} \\
&= 420{,}000 \ \frac{\text{lb coal}}{\text{h}} \text{ x } \frac{4.3 \text{ lb } H_2 - 0.02 \text{ lb } Cl_2}{100 \text{ lb coal}} \\
&\quad \text{x } \frac{\text{lb-mol hydrogen}}{2.016 \text{ lb hydrogen}} \\
&= 8916.7 \text{ lb-mol/h available hydrogen}
\end{aligned}
$$

Since 1/2 mol oxygen is required per mol of hydrogen by Reaction (3), oxygen required is 4458.3 lb-mol/h. Water formed by this reaction, however, is 8916.7 lb-mol/h.

The oxygen content of coal is used in the combustion process as follows:

$$
\begin{aligned}
\text{Oxygen in coal} &= \text{coal charge x oxygen content of coal} \\
&\quad \text{x } \frac{\text{mol oxygen}}{\text{mol. wt. of oxygen}} \\
&= 420{,}000 \ \frac{\text{lb coal}}{\text{h}} \text{ x } \frac{7.3 \text{ lb oxygen}}{100 \text{ lb coal}} \\
&\quad \text{x } \frac{\text{lb-mol oxygen}}{31.998 \text{ lb oxygen}} \\
&= 958.2 \text{ lb-mol/h oxygen}
\end{aligned}
$$

Because of this oxygen contained in coal, less air is required for combustion reactions. Therefore, the theoretical oxygen required for combustion of 420,000 lb/h of coal is the sum of the oxygen required for carbon, sulfur, and hydrogen oxidations minus the amount of oxygen in coal.

Thus,

$$
\begin{aligned}
\text{Theoretical } O_2 \text{ requirement} &= (21{,}393.4 + 458.5 + 4458.3 - 958.2) \ \frac{\text{lb-mol}}{\text{h}} \\
&= 25{,}352 \text{ lb-mol/h.}
\end{aligned}
$$

Theoretical air requirements are calculated as follows. Since dry air contains 21 mol percent oxygen,* the theoretical amount of air required for combustion of 420,000 lb/h of coal is

$$\text{Theoretical dry air requirement} = \text{mol oxygen} \times \frac{100 \text{ mol dry air}}{21 \text{ mol } O_2}$$

$$= 25{,}352 \frac{\text{lb-mol } O_2}{\text{h}} \times \frac{100 \text{ lb-mol air}}{21 \text{ lb-mol } O_2}$$

$$= 120{,}723.8 \text{ lb-mol/h dry air}$$

The amounts of excess air to be supplied to the boiler-furance and to the air heater are assumed to be 20 percent and 40 percent of the theoretical air requirement, respectively (Section 2.3.2 and Table 2.3-6).

Thus,

$$\text{Dry air supplied to boiler-furnace in Stream 3} = \text{theoretical air requirement} \times \frac{120 \text{ mol air}}{100 \text{ mol air}}$$

$$= 120{,}723.8 \frac{\text{lb-mol dry air}}{\text{h}} \times \frac{120 \text{ lb-mol air}}{100 \text{ lb-mol air}}$$

$$= 144{,}868.6 \text{ lb-mol/h dry air}$$
$$= 4{,}179{,}600 \text{ lb/h of dry air}$$

$$\text{Dry air supplied to air heater in Stream 2} = \text{theoretical air requirement} \times \frac{140 \text{ mol air}}{100 \text{ mol air}}$$

$$= 120{,}723.8 \frac{\text{lb-mol dry air}}{\text{h}} \times \frac{140 \text{ lb-mol air}}{100 \text{ lb-mol air}}$$

$$= 169{,}013.3 \text{ lb-mol/h dry air}$$
$$= 4{,}876{,}200 \text{ lb/h dry air}$$

In the air heater, balance air between Streams 2 and 3 leaks to Stream 5. Thus,

$$\text{Air leaks to Stream 5} = (\text{Air supplied to Stream 2}) - (\text{Air supplied to Stream 3})$$

$$= (4{,}876{,}200 - 4{,}179{,}600) \text{ lb/h dry air}$$
$$= 696{,}600 \text{ lb/h dry air}$$
$$\text{or} = 24{,}144.7 \text{ lb-mol/h dry air}$$

2.3.4.5 Moisture Balance--

To complete the material balance, one must know the weight of moisture in the gaseous products, which comes from free moisture in coal, from available hydrogen in coal, and from moisture introduced with the air.

---

* A more accurate value is 20.99 percent [International Critical Tables, Vol. 1, p. 393 (1926)]. The 0.04 percent of CO_2, H_2, and rare gases may be ignored in combustions calculations. Therefore, a commonly used air composition is 70 percent N_2 and 21 percent O_2. The weight of 1 mol of air is 28.851.

$$\text{Free moisture in coal} = \text{Coal charged} \times \text{moisture content of coal} \times \frac{\text{mol water}}{\text{mol. wt. of water}}$$

$$= 420{,}000\ \frac{\text{lb coal}}{\text{h}} \times \frac{8.5\ \text{lb water}}{100\ \text{lb coal}} \times \frac{\text{lb-mol water}}{18.015\ \text{lb water}}$$

$$= 1981.7\ \text{lb-mol/h of water}$$

The moisture from available hydrogen in coal has been calculated in the oxygen requirements; the value is 8916.7 lb-mol/h water since 1 mol of H_2 forms 1 mol of water.

In the calculation of moisture introduced with dry air, year-round average condition of air is assumed to be 70°F and 80 percent relative humidity (Section 2.3.2). Since the weight of dry air is known, the moisture content of air can be computed from the molal humidity, H (lb water per lb dry air), expressed as:

$$H = \frac{\text{mol. wt. of water}}{\text{weight of 1 mol}} \times \frac{\bar{P}_A}{P - \bar{P}_A} \qquad \text{(Eq. 1)}$$

where $\bar{P}_A$ = partial pressure of water vapor, psi

and P = total pressure (14.696 psi)

The partial pressure of water vapor in air can be calculated from the relative humidity, H_R, defined as the ratio of the partial pressure of the water vapor to the vapor pressure of water at air temperature. By definition,

$$H_R = 100\ \frac{\bar{P}_A}{P_A} \qquad \text{(Eq. 2)}$$

where P_A = vapor pressure of water

The vapor pressure of water, P_A, at 70°F is 0.3631 psi. Therefore, $\bar{P}_A$ is 80 percent of P_A and may be calculated from Eq. 2 as follows:

$$\bar{P}_A = P_A \times \frac{H_R}{100} = 0.3631\ \text{psi} \times \frac{80\%}{100\%} = 0.290\ \text{psi}$$

and the humidity, H, from Eq. 1 is

$$H = \frac{28.015 \text{ lb water}}{28.851 \text{ lb dry air}} \times \frac{0.290 \text{ psi}}{14.696 \text{ psi} - 0.290 \text{ psi}}$$

$$= 0.01257 \text{ lb water/lb dry air.}$$

The moisture introduced in air to the boiler-furnace (Stream 3) is calculated as follows:

$$\begin{array}{c}\text{Moisture in}\\ \text{Stream 3}\end{array} = \text{Molal humidity} \times \begin{array}{c}\text{weight of dry air}\\ \text{in Stream 3}\end{array}$$

$$= 0.01257 \frac{\text{lb water}}{\text{lb dry air}} \times 4{,}179{,}600 \frac{\text{lb dry air}}{\text{h}}$$

$$\cong 52{,}500 \text{ lb/h of water} \times \frac{\text{lb-mol water}}{18.015 \text{ lb water}}$$

$$= 2916.3 \text{ lb-mol/h of water}$$

The moisture in air to the air heater (Stream 2) is calculated as follows:

$$\begin{array}{c}\text{Moisture in}\\ \text{Stream 2}\end{array} = \text{Molal humidity} \times \begin{array}{c}\text{weight of dry air}\\ \text{in Stream 2}\end{array}$$

$$= 0.01257 \frac{\text{lb water}}{\text{lb dry air}} \times 4{,}875{,}200 \frac{\text{lb dry air}}{\text{h}}$$

$$\cong 61{,}300 \text{ lb/h of water} \times \frac{\text{lb-mol water}}{18.015 \text{ lb water}}$$

$$= 3402.7 \text{ lb-mol/h of water}$$

The moisture in the gaseous products (Stream 4) is calculated as follows:

$$\begin{array}{c}\text{Moisture in}\\ \text{Stream 4}\end{array} = \begin{array}{c}\text{Free moisture}\\ \text{in coal}\end{array} + \begin{array}{c}\text{Moisture from}\\ \text{available hydrogen}\\ \text{in coal}\end{array} + \begin{array}{c}\text{Moisture}\\ \text{in Stream 3}\end{array}$$

$$= (1981.7 + 8916.7 + 2916.3) \frac{\text{lb-mol water}}{\text{h}}$$

$$= 13{,}814.7 \text{ lb-mol/h water}$$

$$\text{or} = 248{,}900 \text{ lb/h water}$$

Since it is assumed that some of the air supplied to the air heater leaks to gas Stream 5, the moisture content in Stream 5 increases accordingly, thus:

$$\text{Moisture in Stream 5} = \text{Moisture in Stream 4} + \text{Moisture in Stream 2} - \text{Moisture in Stream 3}$$

$$= (13{,}814.7 + 3402.7 - 2916.3)\ \frac{\text{lb-mol water}}{\text{h}}$$

$$= 14{,}301.1\ \text{lb-mol/h water}$$

$$\text{or} = 257{,}700\ \text{lb/h water}$$

Moisture Balance Summary, Boiler Furnace

Input	lb/h	Output	lb/h
Free moisture in coal (1981.7 lb-mol/h)	37,700	Moisture in gaseous products	248,900
From available H_2 in coal (8916.7 lb-mol/h)	160,700		
Moisture introduced with dry air	52,500		
Total	248,900	Total	248,900

Moisture Balance Summary, Air Heater

Input	lb/h	Output	lb/h
Moisture in gaseous products	248,900	Moisture in flue gas	257,700
Moisture introduced with dry air	61,300	Moisture in dry air leaving	52,500
Total	310,200	Total	310,200

2.3.4.6 Nitrogen Balance--

Nitrogen balance of the boiler-furnace is represented by an input consisting of the nitrogen in coal charged plus the nitrogen in air supplied in Stream 3 and an output consisting of the nitrogen in gaseous products (Stream 4). Thus,

$$\text{Nitrogen in coal charged} = \text{Coal charged} \times \text{Nitrogen content of coal}$$

$$= 420{,}000\ \frac{\text{lb coal}}{\text{h}} \times \frac{1.2\ \text{lb nitrogen}}{100\ \text{lb coal}}$$

$$= 5040\ \text{lb/h nitrogen}$$

$$\text{or} \times \frac{\text{lb-mol nitrogen}}{28.014\ \text{lb nitrogen}} = 179.9\ \frac{\text{lb-mol nitrogen}}{\text{h}}.$$

$$\text{Nitrogen in air supplied in Stream 3} = \text{Dry air in Stream 3} \times \frac{79\ \text{mol nitrogen}}{100\ \text{mol dry air}}$$

$$= 144{,}868.6\ \frac{\text{lb-mol dry air}}{\text{h}}$$

$$= 114{,}446.2\ \text{lb-mol/h nitrogen}$$

$$\text{or} = 3{,}206{,}100\ \text{lb/h nitrogen}$$

$$\text{Nitrogen in gaseous products (Stream 4)} = \text{Nitrogen in coal charged} + \text{Nitrogen in air in Stream 3}$$

$$= (179.9 + 114{,}446.2)\ \text{lb-mol/h nitrogen}$$

$$= 114{,}626.1\ \text{lb-mol/h nitrogen}$$

$$\text{or} \times \frac{28.014\ \text{lb nitrogen}}{\text{lb-mol nitrogen}}$$

$$= 3{,}211{,}100\ \text{lb/h nitrogen}$$

$$\text{Nitrogen Stream 5} = \text{nitrogen in Stream 4} + \text{dry air leaks to Stream 5} \times \frac{79\ \text{mol nitrogen}}{100\ \text{mol dry air}}$$

$$= 114{,}626.1\ \frac{\text{lb-mol nitrogen}}{\text{h}} + 24{,}144.7\ \frac{\text{lb-mol dry air}}{\text{h}}$$

$$\times \frac{79\ \text{lb-mol nitrogen}}{100\ \text{lb-mol dry air}}$$

$$= 133{,}700\ \text{lb-mol/h nitrogen}$$

$$\text{or} \times \frac{28.017\ \text{lb nitrogen}}{\text{lb-mol nitrogen}} = 3{,}745{,}500\ \text{lb/h nitrogen}$$

Nitrogen Balance Summary

Input	lb/h	Output	lb/h
Nitrogen in coal	5,000	Nitrogen in gaseous products	3,211,100
Nitrogen in air supplied	3,206,100		
Total	3,211,100	Total	3,211,100

2.3.4.7 Oxygen Balance--

In the oxygen balance of a boiler-furnace, the input consists of free oxygen in coal charged, oxygen in dry air supplied for combustion, oxygen in free moisture in the coal, and oxygen in moisture supplied with the air. The output consists of free oxygen in gaseous products, oxygen in the CO_2 and SO_2 in gaseous products, and oxygen in the moisture in gaseous products. In the calculation of amounts of free oxygen in the gaseous products in Streams 4 and 5, the procedure using these input-output data is not simple. An alternative method is to use the excess oxygen supplied, since this is the only free oxygen in the gaseous products. Thus,

$$\begin{aligned}\text{Oxygen in gaseous products Stream 4} &= \text{Excess oxygen supplied in Stream 3}\\ &= \text{Theoretical oxygen required in the boiler-furnace}\\ &\quad \times \frac{\text{20 mol oxygen}}{\text{100 mol theoretical oxygen}}\\ &= 25{,}352\ \frac{\text{lb-mol}}{\text{h}} \times \frac{\text{20 mol}}{\text{100 mol}}\\ &= 5070.4\ \text{lb-mol/h oxygen}\\ \text{or} \times \frac{\text{31.998 lb oxygen}}{\text{lb-mol oxygen}} &= 162{,}200\ \text{lb/h oxygen}\end{aligned}$$

Oxygen in flue gas (Stream 5) is the sum of the free oxygen in the gaseous products (Stream 4) and the oxygen from the dry air leaks to Stream 5 in the air heater. Therefore,

$$\begin{aligned}\text{Oxygen in Stream 5} &= \text{Oxygen in Stream 4}\\ &\quad + \text{Dry air leaks to Stream 5} \times \frac{\text{21 mol oxygen}}{\text{100 mol dry air}}\\ &= 5070.4\ \frac{\text{lb-mol oxygen}}{\text{h}}\\ &\quad + 24{,}144.7\ \frac{\text{lb-mol dry air}}{\text{h}}\\ &\quad \times \frac{\text{21 lb-mol oxygen}}{\text{100 lb-mol dry air}}\\ &= 10{,}140.8\ \text{lb-mol/h oxygen}\\ \text{or} \times \frac{\text{31.998 lb oxygen}}{\text{lb-mol oxygen}} &= 324{,}500\ \text{lb/h oxygen}\end{aligned}$$

Air at 70°F in Stream 2 consists of 169,013.3 lb-mol/h dry air and 3402.7 lb-mol/h water. Therefore, the volumetric flow rate is

$$\text{Air flow rate} = 359\ \frac{\text{ft}^3 @ 32°\text{F}}{\text{lb-mol air}} \times \frac{(169{,}013.3 + 3402.7)\text{lb-mol}}{\text{h}} \times \frac{(460 + 70)°\text{F}}{(460 + 32)°\text{F}} \times \frac{\text{h}}{60\ \text{min}}$$

$$= 1{,}111{,}300\ \text{ft}^3/\text{min} @ 1\ \text{atm and } 70°\text{F}$$

Following is a summary of the overall material balance around the boiler-furance and air heater.

Material Balance Summary, Boiler-Furnace

Input	lb/h
Weight of coal charged, including free moisture	420,000
Weight of dry air supplied	4,179,600
Weight of moisture in air	52,500
Total	4,652,100
Output	**lb/h**
Weight of dry gaseous products	4,344,400
Weight of moisture in gaseous products	248,900
Weight of refuse, fly ash	47,000
bottom ash	11,800
Total	4,652,100

Material Balance Summary, Air Heater

Input	lb/h
Weight of flue gas including ash and moisture	4,640,300
Weight of dry air supplied	4,876,200
Weight of moisture in air supplied	61,300
Total	9,577,800

Output	lb/h
Weight of dry air leaving	4,179,600
Weight of moisture in air leaving	52,500
Weight of flue gas leaving including ash and moisture	5,345,700
Total	9,577,800

Figure 2.3-17 presents the complete summary of Step 1, the boiler-furance material balance, including air heater balance.

Component balance is also shown.

2.3.5 SO_2 and Particulate Material Balance (Step 2)

In this material balance, the input (Stream 5) consists of the weight of fly ash (47,000 lb/h) and the weight of SO_2 (29,370 lb/h). The output consists of the weight of particulate in the cleaned flue gas, the weight of fly ash removed by ESP (Stream 22), the weight of fly ash removed with sludge, the weight of SO_2 in the cleaned flue gas, and the weight of SO_2 removed by the scrubber as suspended and dissolved solids.

Since the input values are known, calculation begins with the first output item, the weight of particulate in the cleaned flue gas. Under the current NSPS regulation, the maximum allowable particulate emission is 0.1 lb particulate per million Btu heat input. The maximum heat input, Q, into this plant is

$$\begin{aligned} Q &= \text{Coal charged} \times \text{High heating value of coal} \\ &= 420{,}000 \text{ lb/h coal} \times 11{,}150 \text{ Btu/lb coal} \\ &= 4683 \times 10^6 \text{ Btu/h.} \end{aligned}$$

Therefore, the maximum allowable particulate emission, E_P, from this plant is

$$\begin{aligned} E_P &= \frac{0.1 \text{ lb particulate}}{10^6 \text{ Btu heat input}} \times 4683 \times 10^6 \text{ Btu/h heat input} \\ &= 468 \text{ lb/h particulate} \end{aligned}$$

In calculating the weight of fly ash removed by ESP (Stream 22), we consider the minimum allowable fly ash to be removed from this plant. Thus,

$$\begin{array}{c}\text{Minimum allowable}\\\text{fly ash removal}\end{array} = \begin{array}{c}\text{(Total fly ash}\\\text{input)}\end{array} - \begin{array}{c}\text{(Maximum rate of}\\\text{particulate emission)}\end{array}$$

$$= 47{,}000\ \frac{\text{lb fly ash}}{\text{h}} - 468\ \frac{\text{lb particulate}}{\text{h}}$$

$$= 46{,}532\ \text{lb/h fly ash}$$

By the assumption made in Section 2.3.2, the ESP removes 80 percent of the required minimum fly ash removal. Thus,

$$\begin{array}{c}\text{Fly ash removed}\\\text{by ESP}\end{array} = \begin{array}{c}\text{Minimum allowable}\\\text{fly ash removal}\end{array} \times \frac{80\ \text{lb fly ash removed}}{100\ \text{lb fly ash entering}}$$

$$= 46{,}532\ \frac{\text{lb fly ash}}{\text{h}} \times \frac{80\ \text{lb fly ash removed}}{100\ \text{lb fly ash entering}}$$

$$= 37{,}226\ \text{lb fly ash/h}$$

and the minimum ESP efficiency, η_{ESP}, is

$$\eta_{ESP} = \frac{\text{Fly ash removed by ESP}}{\text{Total fly ash input}} \times 100\%$$

$$= \frac{37{,}226\ \text{lb/h fly ash}}{47{,}000\ \text{lb/h fly ash}} \times 100\%$$

$$= 79.21\%.$$

The weight of fly ash removed with sludge is represented by the following balance:

$$\begin{array}{c}\text{Fly ash removed}\\\text{with sludge}\end{array} = \begin{array}{c}\text{Minimum allowable}\\\text{fly ash removal}\end{array} - \begin{array}{c}\text{Fly ash removed}\\\text{by ESP}\end{array}$$

$$= (46{,}532 - 37{,}226)\ \text{lb/h fly ash}$$

$$= 9306\ \text{lb/h fly ash}$$

The minimum allowable particulate removal efficiency, η_p, is

$$\eta_p = \frac{\text{Minimum allowable fly ash removal}}{\text{Total fly ash input}} \times 100\%$$

$$= \frac{46{,}532\ \text{lb/h fly ash}}{47{,}000\ \text{lb/h fly ash}} \times 100\%$$

$$= 99.00\%$$

Next we calculate the weight of SO_3 in the cleaned flue gas. Under the current NSPS regulation, the maximum allowable SO_2 emission is 1.2 lb SO_2/million Btu heat input. Since the maximum heat input, Q, is 4683 x million Btu/h, the maximum allowable SO_2 emission, E_{SO_2}, from this plant is

$$E_{SO_2} = \frac{1.2 \text{ lb } SO_2}{10^6 \text{ Btu heat input}} \times 4683 \times 10^6 \text{ Btu/h heat input}$$

$$= 5620 \text{ lb/h } SO_2$$

The final calculation in the SO_2 and particulate material balance is the final element of output, the weight of SO_2 removed by the scrubber.

$$\begin{array}{c}SO_2 \text{ removed by} \\ \text{scrubber}\end{array} = SO_2 \text{ input} - \begin{array}{c}\text{Maximum allowable} \\ SO_2 \text{ emission}\end{array}$$

$$= (29{,}370 - 5620) \text{ lb/h } SO_2$$

$$= 23{,}750 \text{ lb/h } SO_2$$

$$\text{or} \times \frac{\text{lb-mol } SO_2}{64.058 \text{ lb } SO_2} = 370.76 \text{ lb-mol/h } SO_2$$

Therefore, the minimum allowable SO_2 removal efficiency, η_{SO_2}, is

$$\eta_{SO_2} = \frac{SO_2 \text{ removed by scrubber}}{SO_2 \text{ input}} \times 100\%$$

$$= \frac{23{,}750 \text{ lb/h } SO_2}{29{,}370 \text{ lb/h } SO_2} \times 100\%$$

$$= 80.9\%.$$

The SO_2 and particulate material balance is summarized in Figure 2.3-18.

2.3.6 Slurry Preparation Material Balance/Lime Requirement (Step 3)

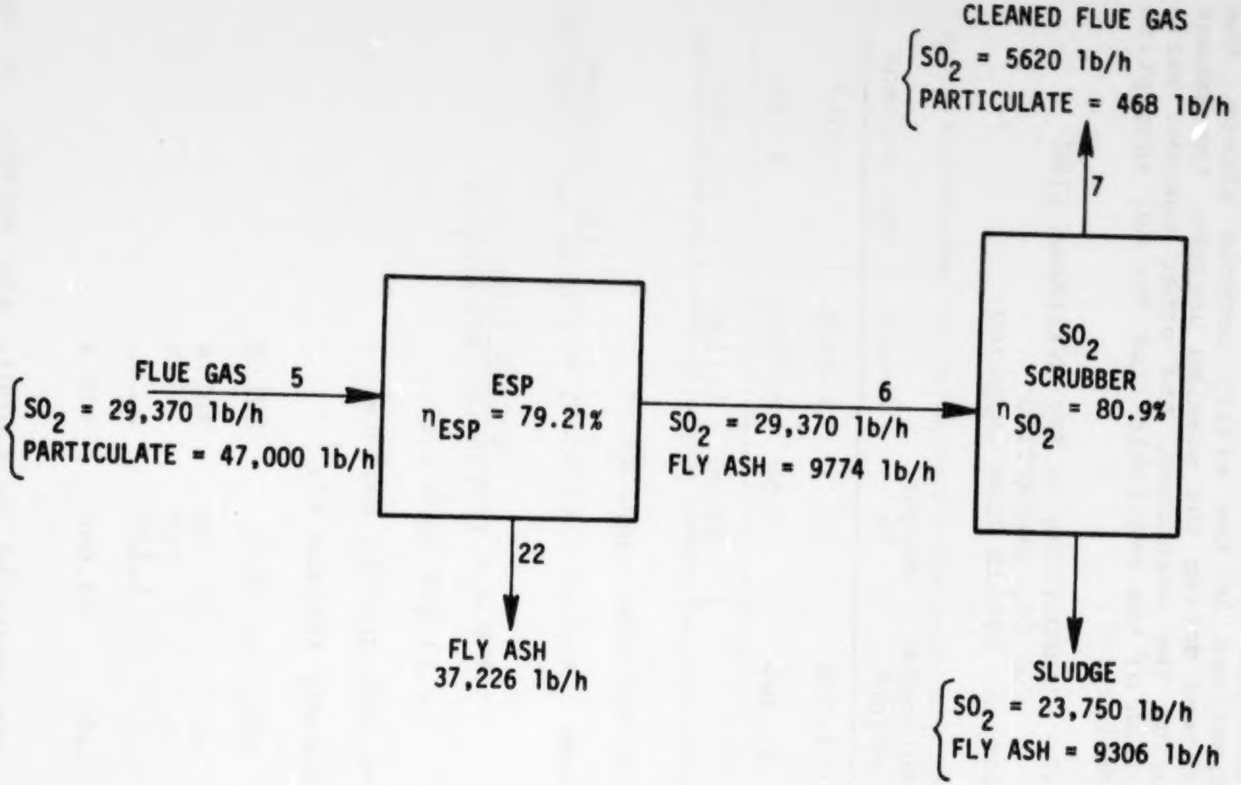
As discussed earlier, the theoretical lime requirement depends on the amount of SO_2 and HCl to be removed from the FGD system (scrubber). In Step 2, this is calculated as 370.76 lb-mol/h SO_2 and 2.4 lb-mol/h HCl. Since 1 mol SO_2 requires 1 mol alkalinity (as CaO and MgO), and 1 mol HCl requires 1/2 mol alkalinity, the theoretical alkalinity requirement is 370.76 + 1.2 = 371.96 lb-mol/h. The actual alkalinity supplied is 110 percent of the theoretical value. Thus,

$$\text{Actual alkalinity} = \text{Theoretical alkalinity} \times \frac{110\%}{100\%}$$

$$= 371.96 \frac{\text{lb-mol}}{\text{h}} \times \frac{110\%}{100\%}$$

$$= 409.2 \text{ lb-mol alkalinity/h,}$$

which is supplied from lime containing 92 percent CaO, 3 percent MgO, and 5 percent grit, as shown in Table 2.3-5.



FLUE GAS
5
SO_2 = 29,370 lb/h
PARTICULATE = 47,000 lb/h
ESP
η_{ESP} = 79.21%
22
FLY ASH
37,226 lb/h
6
SO_2 = 29,370 lb/h
FLY ASH = 9774 lb/h
SO_2
SCRUBBER
η_{SO_2} = 80.9%
7
CLEANED FLUE GAS
SO_2 = 5620 lb/h
PARTICULATE = 468 lb/h
SLUDGE
SO_2 = 23,750 lb/h
FLY ASH = 9306 lb/h

Figure 2.3-18. Summary of SO_2 and particulate material balance.

Part of the excess alkalinity (MgO + CaO) will react with the CO_2. Since the calcium salts are less soluble, the alkalinity will appear as $MgCO_3$. The exact amount of MgO that will react cannot be determined because of lack of information about how much CO_2 is dissolved in the slurry recycle stream, the amount of $Mg(OH)_2$ formed during the slaking process, the amount of $MgSO_3$ formed during the scrubbing, and other unknown variables. The composition of the available lime for SO_2 absorption is summarized in Table 2.3-7.

Table 2.3-7. COMPOSITION OF THE AVAILABLE LIME FOR SO_2 ABSORPTION
(Basis: 100 lb lime supplied)

Component	Molecular weight	Weight, lb	lb-mol	Mol percent
CaO	56.079	92	1.6405	95.662
MgO	40.309	3.00	0.0744	4.338
Total		95.00	1.7149	100.000

The amount of CaO in the lime supplied is

$$\text{CaO in lime} = \text{Actual alkalinity} \times \frac{100 \text{ lb lime}}{1.7149 \text{ mol alkalinity}}$$

$$= 409.2 \times \frac{100 \text{ lb lime}}{1.7149 \text{ mol alkalinity}}$$

$$= 23{,}869 \text{ lb/h lime,}$$

which contains 1190 lb/h grit by balance.

Lime Requirement Summary (Stream 9):

	wt%	lb/h	mol/h
CaO	92	21,950	391.4
MgO	3	720	17.8
Grit	5	1,190	
Total	100	23,860	409.2

2.3.6.1 Slaker--

CaO and MgO are hydrated to $Ca(OH)_2$ and $Mg(OH)_2$ in the slaker, respectively. Hydration also removes 60 percent of the grit from the lime supplied. Thus,

$$\text{Grit removed (Stream 23)} = \text{Total grit in lime supplied} \times \frac{60 \text{ lb grit}}{100 \text{ lb grit}}$$

$$= 1190 \text{ lb/h grit} \times \frac{60 \text{ lb grit}}{100 \text{ lb grit}}$$

$$= 710 \text{ lb/h grit}$$

Since 1 mol CaO or MgO forms 1 mol $Ca(OH)_2$ or $Mg(OH)_2$, the resulting solids from the slaker consist of:

$$Ca(OH)_2 = \text{Total CaO in lime supplied} \times \frac{\text{mol. wt. of } Ca(OH)_2}{\text{lb-mol CaO}}$$

$$= 391.4 \text{ lb-mol/h CaO} \times \frac{74.094 \text{ lb } Ca(OH)_2}{\text{lb-mol CaO}}$$

$$= 29{,}000 \text{ lb/h } Ca(OH)_2,$$

$$Mg(OH)_2 = \text{Total MgO in lime supplied} \times \frac{\text{mol. wt. of } Mg(OH)_2}{\text{lb-mol MgO}}$$

$$= 17.8 \text{ lb-mol/h MgO} \times \frac{58.324 \text{ lb } Mg(OH)_2}{\text{lb-mol MgO}}$$

$$= 1040 \text{ lb/h } Mg(OH)_2,$$

$$\text{Grit in slurry} = \text{Total grit in lime supplied} - \text{Grit removed in slaker}$$

$$= (1190 - 710) \text{ lb/h grit}$$

$$= 480 \text{ lb/h grit}$$

Therefore,

$$\text{Total weight of solids} = Ca(OH)_2 + Mg(OH)_2 + \text{Grit in slurry}$$
$$= (29{,}000 + 1040 + 480) \text{ lb/h}$$
$$= 30{,}520 \text{ lb/h solids},$$

which consists of 35 percent of the slurry from the slaker.

The water content of the slaker slurry is

$$\text{Water content in slaker slurry} = \text{Total weight of solids} \times \frac{65 \text{ lb water}}{35 \text{ lb solids}}$$

$$= 30{,}520 \text{ lb/h solids} \times \frac{65 \text{ lb water}}{35 \text{ lb solids}}$$

$$= 56{,}680 \text{ lb/h water}$$

Therefore, total water requirement (Stream 10) in the slaker is

$$\begin{aligned}
\text{Total water requirement} &= \text{Water required for hydration} + \text{water content in slaker slurry} \\
&= \left(\text{Hydration for CaO} + \text{Hydration for MgO}\right) \times \frac{\text{mol. wt. of water}}{\text{lb-mol water}} \\
&\quad + \text{Water content in slaker slurry} \\
&= (391.4 + 17.9)\ \frac{\text{lb-mol water}}{\text{h}} \times \frac{18.015\ \text{lb water}}{\text{lb-mol water}} \\
&\quad + 56{,}680\ \frac{\text{lb water}}{\text{h}} \\
&= 64{,}050\ \text{lb/h water}
\end{aligned}$$

It is often convenient to convert the mass flow rate unit to volumetric flow rate. The conversion factor is

$$\begin{aligned}
\frac{\text{gal}}{\text{min}} &= \frac{\text{lb solution}}{\text{h}} \times \frac{\text{ft}^3}{62.4\ \text{lb} \times \text{sp. gr.}} \times \frac{7.48\ \text{gal}}{\text{ft}^3} \times \frac{\text{h}}{60\ \text{min}} \\
&= \frac{\text{lb solution}}{\text{h}} \times \frac{0.00200}{\text{sp. gr.}}
\end{aligned}$$

Material Balance Summary, Slaker

Input	lb/h	Output	lb/h
CaO	21,950	$Ca(OH)_2$	29,000*
MgO	720	$Mg(OH)_2$	1,040*
Grit	1,146	Grit in slurry	480
Subtotal (Stream 9)	23,816	Water	56,680
		Subtotal (Stream 16)	87,200
Water (Stream 10)	64,050	Grit removed (Stream 23)	710
Total	87,866	Total	87,910

2.3.6.2 Slurry Feed Tank--

Thirty five percent lime slurry is diluted to 20 percent with a portion of recovered water in a slurry feed tank, as discussed in Section 2.3.2.

Since 20 percent lime slurry contains the same amount of solids as the 35 percent slurry, the weight of the 20 percent slurry is

---

* Values in the output calculations were rounded; thus, the totals of input and output are not equal.

$$\text{Weight of 20\% slurry} = \text{Weight of solids in 35\% slurry} \times \frac{\text{100 lb 20\% slurry}}{\text{20 lb solids}}$$

$$= \text{30,520 lb/h solids} \times \frac{\text{100 lb 20\% slurry}}{\text{20 lb solids}}$$

$$= \text{152,600 lb/h 20\% slurry}$$

The water content of the 20 percent slurry is 122,080 lb/h water by balance (152,600 - 30,520).

The amount of recovered water required for dilution (Stream 13) is

$$\text{Recovered water requirement} = \text{Weight of 20\% slurry} - \text{Weight of 35\% slurry}$$

$$= \text{(152,600 - 87,200) lb/h water}$$

$$= \text{65,400 lb/h water}$$

Material Balance Summary, Slurry Feed Tank

Input	lb/h	Output (Stream 17)	lb/h
$Ca(OH)_2$	29,000	$Ca(OH)_2$	29,000
$Mg(OH)_2$	1,040	$Mg(OH)_2$	1,040
Grit	480	Grit	480
Total solids	30,520	Total solids	30,520
Water in 35% slurry	56,680	Water in 25% slurry	122,080
Subtotal (Stream 16)	87,200		
Recovered water (Stream 13)	65,400		
Total	152,600	Total	152,600

A complete summary of the slurry preparation material balance is presented in Figure 2.3-19.

2.3.7 Scrubber Material Balance (Step 4)

2.3.7.1 Waste Slurry Calculation--

Input data consist of the following:

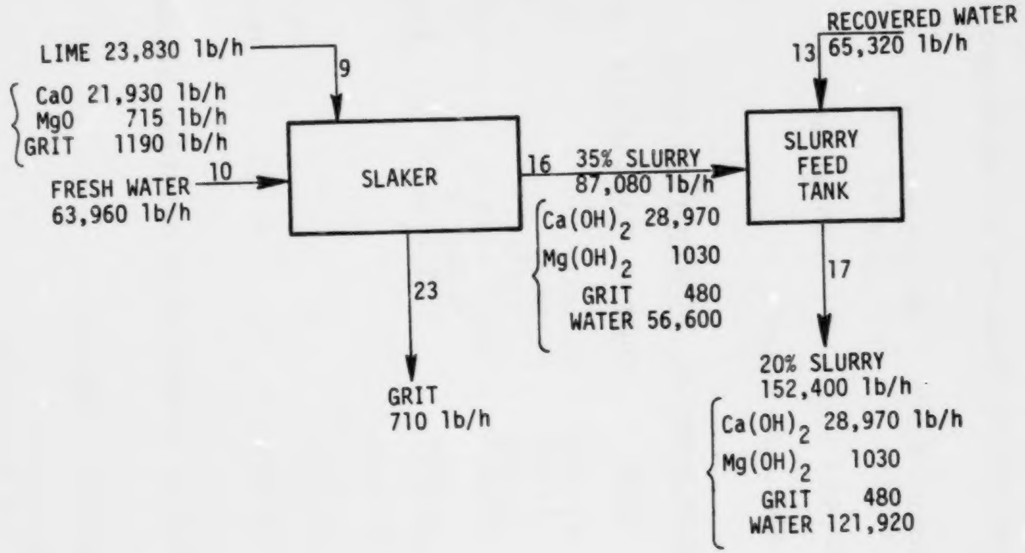

LIME 23,830 lb/h
CaO 21,930 lb/h
MgO 715 lb/h
GRIT 1190 lb/h
9
FRESH WATER
63,960 lb/h
10
SLAKER
23
GRIT
710 lb/h
16
35% SLURRY
87,080 lb/h
Ca(OH)2 28,970
Mg(OH)2 1030
GRIT 480
WATER 56,600
RECOVERED WATER
13
65,320 lb/h
SLURRY
FEED
TANK
17
20% SLURRY
152,400 lb/h
Ca(OH)2 28,970 lb/h
Mg(OH)2 1030
GRIT 480
WATER 121,920

Figure 2.3-19. Summary of slurry preparation material balance.

Available alkalinity for SO_2 removal

$Ca(OH)_2$ = 391.4 lb-mol/h
$Mg(OH)_2$ = 17.8 lb-mol/h

Total = 409.2 lb-mol/h

Other

Grit = 480 lb/h
$Mg(OH)_2$ for forming $MgCO_3$ = 0.89 lb-mol/h
Ash = 936 lb/h

Since total SO_2 + HCl/2 to be removed is 372.0 lb-mol/h, the excess alkalinity is 409.2 - 372.0 = 37.2 lb-mol/h.

Sulfite formation:

(1) $MgSO_3$ formed by Reaction 5 as dissolved solids is 17.8 lb-mol/h
(2) $CaSO_3$ formed by Reaction 7 = 354.2 lb-mol/h

Twenty percent oxidation of sulfite to sulfate:

(1) $CaSO_4$ formed by Reaction 8 = 354.2 lb-mol/h

$$\times \frac{20 \text{ lb-mol } CaSO_4}{100 \text{ lb-mol } CaSO}$$

3

= 70.84 lb-mol/h

(2) $CaSO_4 \cdot 2H_2O$ crystal formed = 70.84 lb-mol/h (12,200 lb/h)
(3) $CaSO_3$ left in the product = 354.2 - 70.84 = 283.36 lb-mol/h
(4) $CaSO_3 \cdot 1/2H_2O$ crystal formed = 283.36 lb-mol/h (36,600 lb/h)
(5) Oxygen required by the reaction 8 = 1/2 x 70.84 lb-mol/h = 35.42 lb-mol/h = 570 lb/h

$MgCO_3$ formation by Reaction 6:

(1) $Mg(OH)_2$ available for Reaction 6 = 0.89 lb-mol/h
(2) $MgCO_3$ formed = 0.89 lb-mol/h (75 lb/h)
(3) CO_2 consumed = 0.89 lb-mol/h (40 lb/h)

Limestone formation by Reaction 9:

(1) Excess $Ca(OH)_2$ = 37.2 lb-mol/h
(2) $CaCO_3$ formed = 37.2 lb-mol/h (3720 lb/h)
(3) CO_2 consumed = 37.2 lb-mol/h (1640 lb/h)

The solids content of the waste slurry is summarized in Table 2.3-8.

Table 2.3-8. WASTE SLURRY SUSPENDED SOLIDS

Component	Mass flow rate, lb/h	Composition, % (dry basis)
Ash	9,306	14.92
Grit	480	0.77
$CaCO_3$	3,720	5.95
$CaSO_3 \cdot 1/2H_2O$	36,600	58.68
$CaSO_4 \cdot 2H_2O$	12,200	19.56
$MgCO_3$	74	0.12
Total	62,380	100.00

Since the solids content in waste Stream 20 is 14 percent, total waste slurry flow rate is

$$62{,}400 \text{ lb/h suspended solids} \times \frac{100 \text{ lb slurry}}{14 \text{ lb suspended solids}}$$

$$\cong 445{,}500 \text{ lb/h (or} = 819 \text{ gal/min),}$$

and the water content is 383,100 lb/h by balance.

The waste slurry containing 14 percent suspended slurry is introduced into the pond, where the sludge containing 50 percent suspended solids settles and the balance water is recycled to the FGD system.

The resulting material balance is represented in Figure 2.3-20.

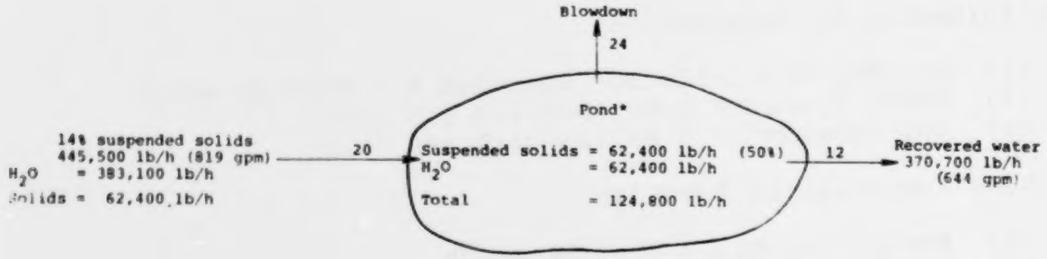

Blowdown
24
Pond*
14% suspended solids
445,500 lb/h (819 gpm)
H_2O = 383,100 lb/h
Solids = 62,400 lb/h
20
Suspended solids = 62,400 lb/h (50%)
H_2O = 62,400 lb/h
Total = 124,800 lb/h
12
Recovered water
370,700 lb/h
(644 gpm)

Figure 2.3-20. Pond material balance.

Stream 24 blowdown is assumed to be zero during normal operation, although some blowdown may be necessary on an intermittent basis to remove chlorides from the system.

It should be noted that the interstitial water in the sludge contains $MgSO_3$ and $CaCl_2$ as dissolved species and remains on the bottom of the pond. The hydrogen chloride introduced into the system will react with the alkalinity. Consequently, the 2.4 lb-mol of hydrogen chloride produced will react to form 1.2 lb-mol of calcium chloride (130 lb/h $CaCl_2$). At steady state, all the calcium chloride introduced (130 lb/h) to the FGD system and 17.8 lb-mol/h $MgSO_3$ (or 1860 lb/h $MgSO_3$) are removed with the interstitial water. The concentrations of the dissolved species are as follows:

$$\text{Concentration of } MgSO_3 = \frac{\text{amount of } MgSO_3 \text{ in the interstitial water}}{\text{weight of solution less suspended solids}}$$

$$= \frac{1860 \text{ lb/h } MgSO_3}{383{,}100 \text{ lb/h solution}} \times 10^6 \text{ ppm}$$

$$= 4{,}855 \text{ ppm } MgSO_3 \text{ as dissolved solids}$$

$$\text{Concentration of HCl} = \frac{\text{amount of } CaCl_2 \text{ in the interstitial water}}{\text{weight of solution less suspended solids}}$$

$$= \frac{130 \text{ lb/h HCl}}{383{,}100 \text{ lb/h solution}} \times 10^6 \text{ ppm}$$

$$= 349 \text{ ppm HCl}$$

Inlet flue gas to the scrubber--The composition of the inlet gas to the scrubber (Stream 6) is the same as the gas leaving the air heater except that 79.21 percent (37,226 lb/h) of the fly ash is removed. The result is presented in Table 2.3-9.

Table 2.3-9. INLET FLUE GAS TO SCRUBBER (STREAM 6)

Components	Flow rate		Composition,[a] wt. %
	lb/h	lb-mol/h	
Ash	9,774		
CO_2	941,600	21,393.4	18.68
HCl	130	1.2	0.00
N_2	3,745,500	133,700.0	74.30
O_2	324,500	10,140.8	6.44
SO_2	29,370	458.5	0.58
H_2O	257,700	14,301.1	
Total	5,308,570	179,995.0	100.00

[a] Dry basis

The volumetric flow rate, V_G, is

$$V_G = \frac{179{,}996.2 \text{ lb-mol flue gas}}{\text{h}} \times \frac{(460 + 285)^\circ\text{F}}{(460 + 32)^\circ\text{F}} \times \frac{359 \text{ ft}_3}{\text{lb-mol}}$$

$$\times \frac{\text{h}}{60 \text{ min}} \times \frac{4039.2 \text{ in. } H_2O}{(4039.2 + 20) \text{ in. } H_2O}$$

$$= 1{,}623{,}000 \text{ acfm at } 285^\circ\text{F}$$

when the gauge pressure of the gas is 20 in. H_2O. The molal humidity of gas, H, is

$$H = \frac{\text{weight of water}}{\text{weight of dry gas}}$$

$$= \frac{257{,}700 \text{ lb water/h}}{5{,}308{,}500 \text{ lb/h flue gas} - 257{,}700 \text{ lb/h water} - 9774 \text{ lb/h ash}}$$

$$= 0.05112 \text{ lb } H_2O/\text{lb dry gas}$$

Outlet gas from the scrubber (Stream 7)--In the scrubber, some SO_2 (23,750/h lb SO_2) and ash (9306 lb/h) are removed by the scrubbing slurry, and some oxygen is consumed to oxidize sulfite to sulfate. Carbon dioxide is also consumed by Reactions 6 and 9. Hydrogen chloride is completely consumed by the excess alkalinity to form calcium chloride.

Therefore, the resulting gas compositions (dry basis) are as follows:

Ash = 9774 lb/h - 9306 lb/h = 468 lb/h ash

CO_2 = 941,600 lb/h - 40 lb/h consumed by Reaction 6 - 1630 lb/h consumed by Reaction 9
= 939,930 lb/h CO_2 (21,357.7 lb-mol/h CO_2)

N_2 = 3,745,500 lb/h (133,700 lb-mol/h N_2)

O_2 = O_2 in inlet flue gas - O_2 consumed in Reaction 8
= 324,500 lb/h O_2 - 570 lb/h O_2
= 323,930 lb/h O_2 (10,123.4 lb-mol/h O_2)

SO_2 = SO_2 in inlet flue gas - SO_2 removed in the scrubber
= 29,370 lb/h SO_2 - 23,750 lb/h SO_2
= 5620 lb/h SO_2 (87.74 lb-mol/h SO_2)

Total = 5,015,400 lb/h flue gas (165,268.84 lb-mol/h)
(dry basis)

Flue gas temperature leaving the scrubber (Stream 7)--Use of a psychrometric chart permits rapid estimation of the humidity and the temperature of the air leaving a scrubbing system.

When unsaturated air is introduced into a scrubbing system, water will evaporate into the air under adiabatic conditions at constant pressure. The wet-bulb temperature remains constant throughout the period of vaporization.

If evaporation continues until the air is saturated with water vapor, the final temperature of the gas will be the same as its initial wet-bulb temperature (dew point).

For example, Figure 2.3-21 shows that the air (point A) is at a temperature of 285°F with humidity of 0.05112 lb water per lb dry air. As vaporization takes place, the molal humidity of air increases but the wet-bulb temperature remains constant. The dry-bulb temperature must correspondingly decrease along the 125°F wet-bulb temperature line (adiabatic cooling line). Therefore, the air leaving the scrubbing system is saturated at a temperature of 125°F. As illustrated here, the psychrometric chart is prepared for the "Air-Water" system.

For gas containing carbon dioxide, a line is established between the lines X = 0 and X = 1.0, depending on the mole fraction (X_1) of the carbon dioxide in the gas. Then a line parallel to this is projected from point A, representing a dry-bulb temperature of 285°F and a humidity of 0.05112, to the saturation curve. The intersection, B, is at a temperature of 126°F, and the molal humidity at this point is 0.09896 lb H_2O/lb dry air.

When a more accurate value is needed, it can be calculated from the water properties and the definition of the saturation humidity, H_s,

$$H_s = \frac{18.015 \text{ lb water}}{28.851 \text{ lb dry air}} \times \frac{P_A}{P - P_A} \qquad \text{(Eq. 3)}$$

where P_A = vapor pressure of water
and P = total pressure

At the saturation temperature of 126°F, P_A = 2.01046 psi. Therefore,

$$H_s = \frac{18.015 \text{ lb water}}{28.851 \text{ lb dry air}} \times \frac{2.01046 \text{ psi}}{(14.696 - 2.01046) \text{ psi}}$$
$$= 0.09896 \text{ lb water/lb dry air}$$

The amount of water vapor in the outlet gas is

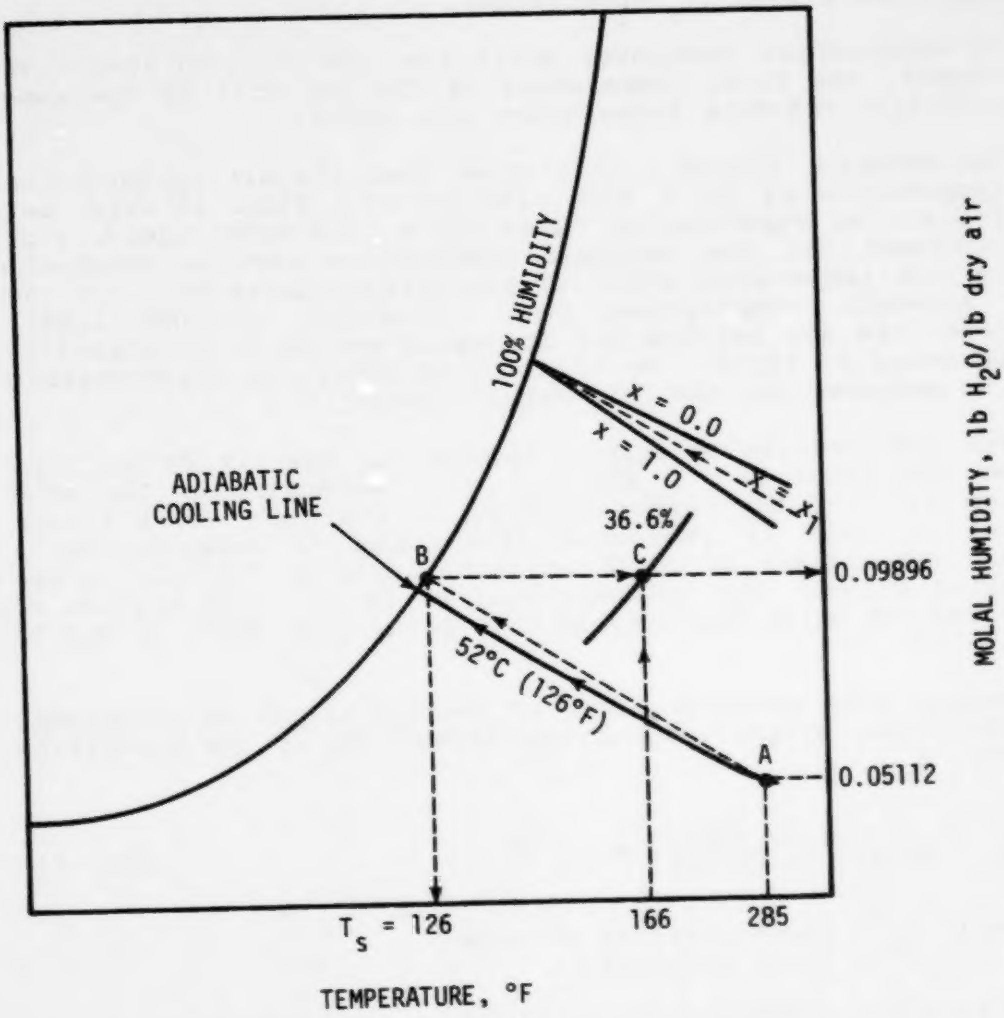


Figure 2.3-21. Psychrometric chart for Example 1 (not to scale).

$$\frac{0.09896 \text{ lb water}}{\text{lb dry gas}} \times 5{,}015{,}400 \text{ lb/h dry gas} = 496{,}300 \text{ lb/h water}$$

or = 27,550.6 lb-mol water

and the total mass flow rate of the gas is

5,015,400 lb/h dry gas + 496,300 lb/h water = 5,511,700 lb/h gas.

The volumetric gas flow rate is

$$\frac{(165{,}268.84 + 27{,}550.6) \text{ lb-mol}}{\text{h}} \times \frac{(460 + 126)°\text{F}}{(460 + 32)°\text{F}} \times \frac{\text{h}}{60 \text{ min}} \times \frac{359 \text{ ft}_3}{\text{lb-mol}} \times \frac{4039.2 \text{ in. } H_2O}{(4039.2 + 6) \text{ in. } H_2O}$$

= 1,372,100 acfm at 126°F

The composition of the cleaned flue gas leaving the scrubber (Stream 7) is summarized in Table 2.3-10.

Table 2.3-10. CLEANED FLUE GAS COMPOSITION (STREAM 7)

Component	Mass flow rate, lb/h	Composition, wt. %
Ash	468	0.0085
CO_2	939,900	17.05
N_2	3,745,500	67.96
O_2	323,900	5.88
SO_2	5,620	0.1020
H_2O	496,300	9.00
Total	5,511,700	100.00

Gas leaving reheater (Stream 8)--Gas flow rate:

$$= 1{,}372{,}100 \text{ acfm} \times \frac{(460 + 166)°\text{F}}{(460 + 126)°\text{F}} \times \frac{4039.2 \text{ in. water}}{(4039.2 + 3) \text{ in. water}}$$

= 1,464,700 acfm at 166°F

This gas contains 445 ppm or 5620 lb/h SO_2.

Relative humidity:

When the gas is heated, the dry-bulb temperature increases, but the molal humidity of the gas remains constant. Therefore, the gas property moves along the dotted line from B to C in

Figure 2.3-21. Point C represents the gas leaving the reheater. The relative humidity at this point can be read from the figure or calculated by Eq. 1, where P_A is the same as the vapor pressure at 126°F, and P_A is the vapor pressure at 166°F. Therefore,

$$H_R = 100\% \times \frac{P_A \text{ at } 126°F}{P_A \text{ at } 166°F} = 100\% \times \frac{2.01046 \text{ psi}}{5.4916 \text{ psi}}$$

$$= 36.6 \text{ percent}$$

1,372,100 acfm $\rightarrow^{7}$ Reheater $\rightarrow^{8}$ 1,464,700 acfm
at 126°F at 166°F
$H_R = 100\%$ $H_R = 36.6\%$

Scrubber slurry flow requirement (Stream 19)--The L/G ratio of the scrubber in this process is given as 40 gal slurry per 1000 ft^3 gas. Since the gas flow rate from the scrubber is 1,372,100, the slurry flow rate, L_S, is

$$L_s = \frac{40 \text{ gal}}{1000 \text{ ft}^3} \times \frac{1{,}372{,}100 \text{ ft}^3}{\text{min}} \times \frac{9.065 \text{ lb}}{\text{gas}} \times \frac{60 \text{ min}}{\text{h}}$$

$$= 29{,}851{,}400 \text{ lb/h of slurry (or } = 54{,}880 \text{ gal/min)},$$

which contains 14 percent suspended solids (or 29,851,400 x 0.14 = 4,179,200 lb/h) and 86 percent water (or 25,672,200 lb/h).

From the flow diagram, Figure 2.3-12, the total slurry flow rate in Stream 18 is the sum of Streams 19 and 20, i.e.:

Stream 18 = Stream 19 + Stream 20
= 29,851,400 lb/h slurry + 445,500 lb/h waste slurry
= 30,296,900 lb/h slurry (55,700 gal/min),

which contains 4,241,600 lb/h suspended solids (14%) and 26,055,300 lb/h water (excluding water in the crystals).

Water requirement--The total water requirement to the scrubber and the recycle tank can be calculated from the overall material balance of the above equipment. Therefore, in Figure 2.3-12, the sum of inputs by Streams 6, 11, 14, 15, and 17 should be balanced with that of outputs by Streams 7 and 20.

Streams (6 + 11 + 14 + 15 + 17) = Streams (7 + 20) (Eq. 4) where the flow rates are

Stream 6 = 5,308,500 lb/h,
Stream 17 = 152,600 lb/h,
Stream 7 = 5,511,700 lb/h,
Stream 20 = 445,500 lb/h.

Streams (11 + 14 + 15) are the total water requirement to the scrubber and recycle tank. From equation 4,

Streams (11 + 14 + 15) = Streams (7 + 20 - 6 - 17)
= 5,511,700 + 445,500 - 5,308,500 - 152,600
= 496,100.

Since Stream 15 is set at 150,000 lb/h for mist eliminator washing water from the recovered water,*

Streams (11 + 14) = (496,100 - 150,000) lb/h
= 346,100 lb/h

The flow rate in Stream 14 can be calculated from the recovered water balance in Step 5. The result, however, is presented in Figure 2.3-22 for convenience.

2.3.8 Water Balance (Step 5)

Water input to the absorber and the recycle tank system consists of the following:

Stream 6: Water in the flue gas to the scrubber (257,700 lb/h)
Stream 11: Fresh makeup water
Stream 14: Recovered water to the recycle tank
Stream 15: Demister wash water from the recovered water to the scrubber-absorber (150,000 lb/h)
Stream 17: Water in the feed slurry (122,080 lb/h)

Water output from the scrubber and the recycle tank system is as follows:

Stream 7: Water carried out by flue gas (496,300 lb/h)
Stream 20: Water in the waste slurry (383,100 lb/h)

Recovered water to the recycle tank (Stream 14) is calculated as follows:

Stream 14 = Stream 12 - (Streams 13 + 15)
= 320,700 lb/h - (65,400 lb/h + 150,000 lb/h)
= 105,300 lb/h (or 211 gal/min)

---

* Note that the recovered water contains 4855 ppm $MgSO_3$ and 235 ppm HCl as dissolved species.

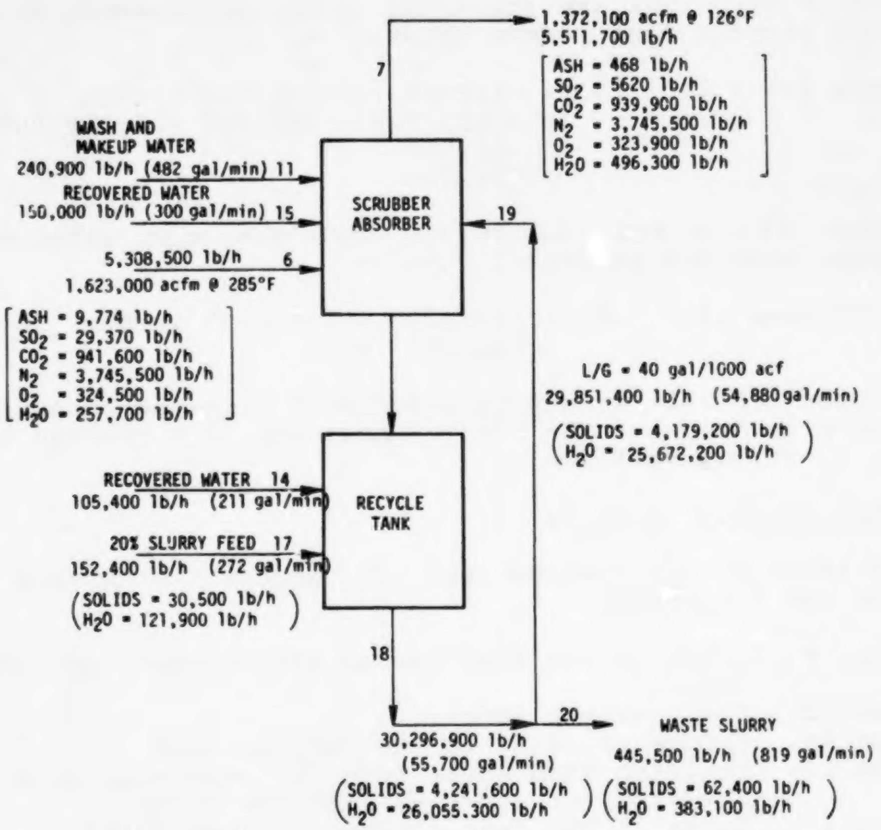

1,372,100 acfm @ 126°F
5,511,700 lb/h
ASH = 468 lb/h
SO_2 = 5620 lb/h
CO_2 = 939,900 lb/h
N_2 = 3,745,500 lb/h
O_2 = 323,900 lb/h
H_2O = 496,300 lb/h
7
WASH AND MAKEUP WATER
240,900 lb/h (482 gal/min) 11
RECOVERED WATER
150,000 lb/h (300 gal/min) 15
SCRUBBER ABSORBER
19
5,308,500 lb/h 6
1,623,000 acfm @ 285°F
ASH = 9,774 lb/h
SO_2 = 29,370 lb/h
CO_2 = 941,600 lb/h
N_2 = 3,745,500 lb/h
O_2 = 324,500 lb/h
H_2O = 257,700 lb/h
L/G = 40 gal/1000 acf
29,851,400 lb/h (54,880 gal/min)
(SOLIDS = 4,179,200 lb/h
H_2O = 25,672,200 lb/h)
RECOVERED WATER 14
105,400 lb/h (211 gal/min)
RECYCLE TANK
20% SLURRY FEED 17
152,400 lb/h (272 gal/min)
(SOLIDS = 30,500 lb/h
H_2O = 121,900 lb/h)
18
20
WASTE SLURRY
30,296,900 lb/h
(55,700 gal/min)
445,500 lb/h (819 gal/min)
(SOLIDS = 4,241,600 lb/h
H_2O = 26,055,300 lb/h)
(SOLIDS = 62,400 lb/h
H_2O = 383,100 lb/h)

Figure 2.3-22. Summary of scrubber material balance.

Fresh makeup water (including pump seals) is the water in Stream 11. The sum of Streams 11 and 14 is 346,100 lb/h. Stream 14 is known to be 105,300 lb/h. The calculation therefore is,

Stream 11 = Streams (11 + 14) - Stream 14
= (346,100 - 105,300) lb/h
= 240,800 lb/h fresh water (482 gal/min)

The total freshwater requirement consists of freshwater for the slaker (Stream 10) plus fresh makeup water (Stream 11). Thus,

= 65,000 lb/h + 240,800 lb/h
= 304,800 lb/h of freshwater (or = 610 gal/min)

The results are summarized in Figure 2.3-23.

2.3.9 Information on Several Operable Lime Absorber Systems on Utility Boilers

This section describes six operating lime absorber systems in use on utility boilers. Following an introduction to each plant is a description of the FGD system and its major components, together with a flow diagram. This information is representative of the lime processes and equipment now in use.

2.3.9.1 Bruce Mansfield Station, Pennsylvania Power Co.--

Introduction--The Bruce Mansfield plant of Pennsylvania Power is a 2700-MW, three-boiler, coal-fired facility located on the Ohio River in Shippingport, Pennsylvania. This facility was built by Pennsylvania Power Co., which is acting on its own behalf and as an agent for the other participating companies: Cleveland Electric Illuminating Co., Duquesne Light Co., Ohio Edison Co., and Toledo Edison Co.

Bruce Mansfield Nos. 1, 2, and 3 are once-through, supercritical steam generators that fire 333 ton/h of coal and generate approximately 6.5 million lb/h (each) of steam at 3785 psig and 1005°F.

The units are rated at 825 MW each. The emission control equipment is designed to meet state emission regulations of 0.6 lb SO_2 per million Btu of heat input and 0.0175 gr/scf of particulate when burning 11,900 Btu/lb coal having average ash and sulfur contents of 12.5 and 4.7 percent, respectively. Additional design-related information is presented in Table 2.3-11.

FGD system--The following describes the FGD system for Units 1 and 2 at Bruce Mansfield. Figure 2.3-24 is a flow diagram of the FGD system showing the FGD equipment and connecting mass flows.

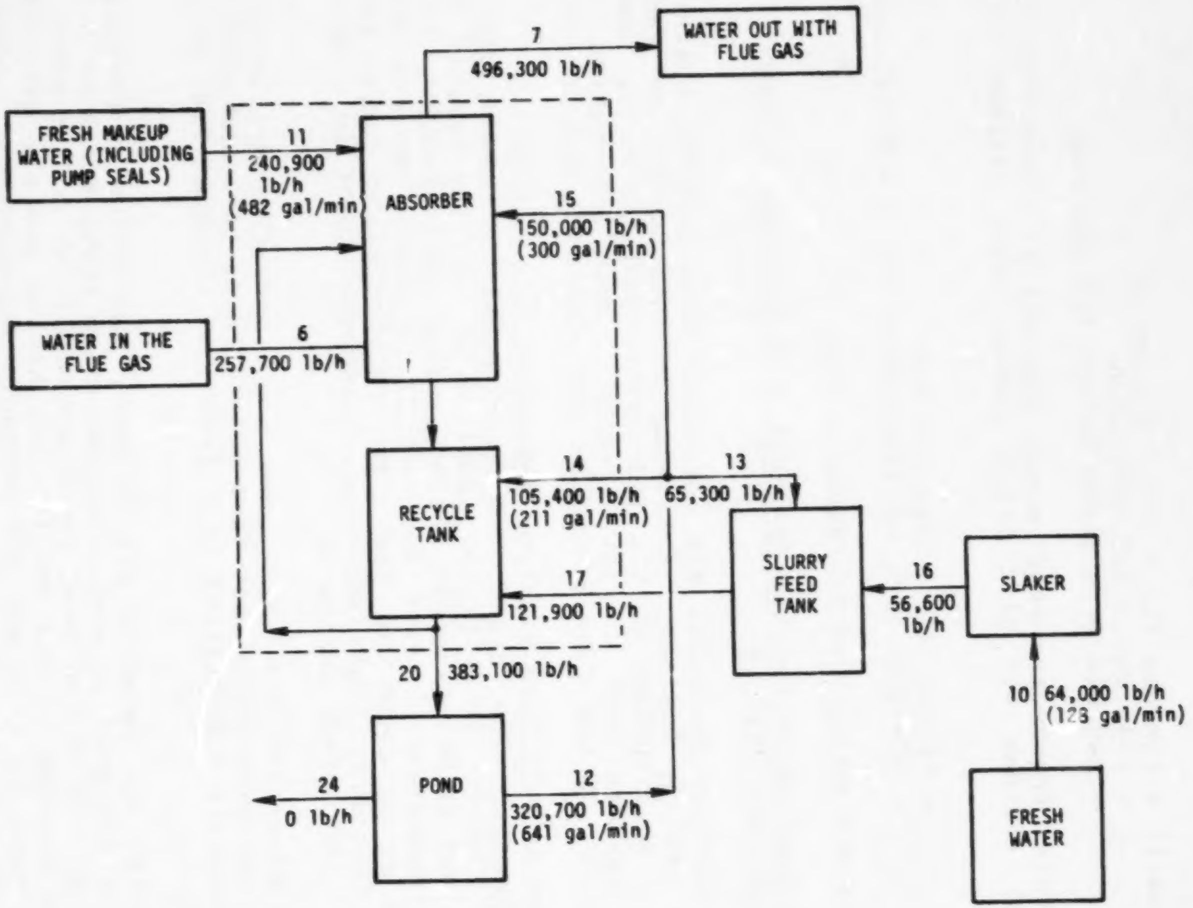

7
496,300 lb/h
WATER OUT WITH FLUE GAS
FRESH MAKEUP WATER (INCLUDING PUMP SEALS)
11
240,900 lb/h (482 gal/min)
ABSORBER
15
150,000 lb/h (300 gal/min)
WATER IN THE FLUE GAS
6
257,700 lb/h
14
105,400 lb/h (211 gal/min)
13
65,300 lb/h
RECYCLE TANK
SLURRY FEED TANK
16
56,600 lb/h
SLAKER
17
121,900 lb/h
20
383,100 lb/h
10
64,000 lb/h (123 gal/min)
24
0 lb/h
POND
12
320,700 lb/h (641 gal/min)
FRESH WATER

Figure 2.3-23. Water balance summary.

Table 2.3-11. DESIGN BOILER AND FUEL DATA FOR BRUCE MANSFIELD NOS. 1, 2, AND 3

Data	Item
Boiler manufacturer	Foster-Wheeler
Year placed in service	No. 1 (1976), No. 2 (1977), No. 3 (in construction)
Gross plant rating/unit	917 MW
Net plant rating/unit	825 MW
Heat rate at 825 MW	10,000 Btu/kWh
Heat input/unit	8,055 million Btu/h
Boiler load range, % of capacity	25-100
Flue gas flow rate (full load)/unit	3,308,000 acfm
Sulfur content of coal	4.7%
Ash content of coal	12.5%
Heating value of coal	11,900 Btu/lb

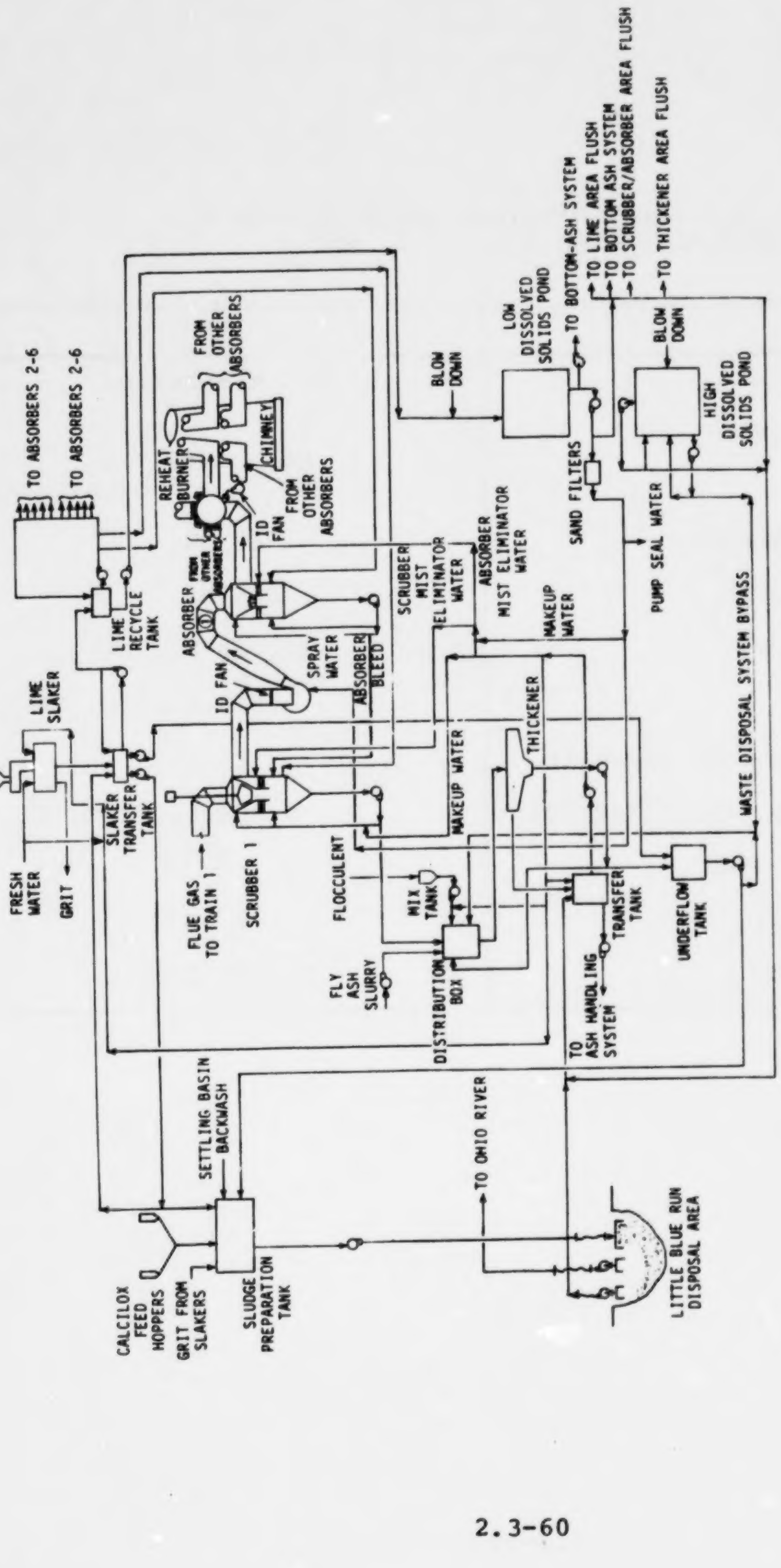

TO ABSORBERS 2-6
TO ABSORBERS 2-6
DAY SILO
LIME SLAKER
FRESH WATER
GRIT
SLAKER TRANSFER TANK
LIME RECYCLE TANK
REHEAT BURNER
CHIMNEY
FROM OTHER ABSORBERS
FROM OTHER ABSORBERS
FROM OTHER ABSORBERS
ID FAN
ID FAN
ABSORBER
FLUE GAS TO TRAIN 1
SCRUBBER 1
SPRAY WATER
ABSORBER BLEED
SCRUBBER MIST ELIMINATOR WATER
ABSORBER MIST ELIMINATOR WATER
MAKEUP WATER
MAKEUP WATER
FLOCCULENT
MIX TANK
FLY ASH SLURRY
DISTRIBUTION BOX
THICKENER
TRANSFER TANK
TO ASH HANDLING SYSTEM
UNDERFLOW TANK
WASTE DISPOSAL SYSTEM BYPASS
PUMP SEAL WATER
SAND FILTERS
BLOW DOWN
LOW DISSOLVED SOLIDS POND
BLOW DOWN
HIGH DISSOLVED SOLIDS POND
TO BOTTOM-ASH SYSTEM
TO LIME AREA FLUSH
TO BOTTOM ASH SYSTEM
TO SCRUBBER/ABSORBER AREA FLUSH
TO THICKENER AREA FLUSH
SETTLING BASIN BACKWASH
CALCILOX FEED HOPPERS
GRIT FROM SLAKERS
SLUDGE PREPARATION TANK
TO OHIO RIVER
LITTLE BLUE RUN DISPOSAL AREA

Figure 2.3-24. Simplified flow diagram of Bruce Mansfield

Unit 1 began full commercial operation on June 1, 1976, and Unit 2, on October 1, 1977. Six separate venturi scrubber and venturi SO_2 absorber trains service each boiler. The system was designed and furnished by Chemico Air Pollution Control Company. The system utilizes the Dravo Corporation's thiosorbic lime* as the SO_2 absorbent. Both units are guaranteed to remove 92 percent of the sulfur dioxide, and 99.8 percent of the particulate matter from the flue gas.

Unit 3, now under construction, will be equipped with a Kellogg/ Weir absorber, a horizontal, cross-flow spray unit that can be operated at a flue gas velocity above 20 ft/s. The FGD system will operate at 25 to 100 percent boiler capacity and no bypass will be provided. Continued operation is ensured by an extra absorbing stage on each module and by one entire spare module. Estimated startup is April 1980.

Scrubber--Each scrubbing train consists of a variable-throat, a particulate scrubbing venturi, a 9000-hp induced-draft (ID) fan, and a fixed-throat venturi absorber in series. There are six scrubber trains per boiler. The variable-throat venturi removes most of the particulates. Additional particulate removal is accomplished in the absorber. Sulfur dioxide is absorbed in both the particulate scrubber and the absorber. The scrubber vessels are 35.5 ft in diameter and 52 ft high, with a "plumb-bob" arrangement for the variable-throat mechanism. The absorber vessels are 34 ft in diameter and 51.5 ft high. The scrubber and absorber vessels are lined with polyester flakeglass material. The ID fan housing is lined with rubber and the fan rotors are made of Inconel 625. Information regarding the venturi-scrubber and absorber is given in Table 2.3-12.

FGD system tanks--The FGD tank system consists of the slaker transfer, lime recycle, distribution box, transfer, underflow, and sludge preparation tanks.

Lime is fed directly by belts from day silos into two lime slakers having maximum lime-slurry capacities of 100 gal/min. The slaked lime is pumped to the 36-ft-diameter slaker transfer tank, where it is retained for about half an hour. This tank helps complete the lime slaking. The slurry is pumped to the 12-ft-diameter lime recycle tank located 3000 ft from the slakers. The recycle tank supplies fresh slurry to each of the scrubber and absorber vessels via individual branches. A portion of the spent slurry is bled to the distribution box--a mixing tank with zero-time retention. Here the slurry is mixed with flocculant and fly ash slurry from the boiler prior to entering the 200-ft-diameter thickener. Overflow from the thickener goes to the transfer tank for reuse in the fly ash

---

* Dravo's patented lime contains 6 to 12 percent magnesium oxide.

Table 2.3-12. BRUCE MANSFIELD SCRUBBER AND ABSORBER DATA

Data	Item
Particulate scrubber	
Manufacturer	Chemico Air Pollution Control Company
Type	Variable throat venturi
L/G ratio	40 gal/1000 acfm
Scrubber pressure drop across throat	25 in. H_2O
Dimensions	35.5 ft dia., 52 ft high
SO_2 absorber	
Manufacturer	Chemico Air Pollution Control Company
Type	Fixed-throat venturi
L/G ratio	40 gal/1000 acfm
Absorber pressure drop across throat	4-7 in. H_2O
Dimensions	34 ft dia., 51.5 ft high

recovery system. Sludge from the thickener (30% solids) is pumped to the adjacent 10,500-gal underflow tank, where the sludge is pumped to the waste disposal system or to the onsite ponds in emergency cases.

At the waste disposal area, two 100-ton hoppers (12 ft dia. x 24 ft high) distribute Calcilox to the 176,000-gal sludge preparation tanks (35 ft dia. x 35 ft high) before the sludge is pumped to the Little Blue Run disposal site.

Reheat--Three absorber outlets combine into a single reheat chamber. For each boiler there are two 25-ft-diameter reheat chambers. The flue gas is reheated by three fuel-oil burners from about 126°F to the designed 165°F before it exits through the stack. Pennsylvania Power Company has yet to use the reheaters because of duct vibrations caused by resonance. The reheaters are being redesigned to correct the resonance problem. Plume buoyancy appears to be sufficient without reheat, but atmospheric conditions sometimes cause condensation and precipitation of moisture from the plume. Predominating winds often cause liquid fallout to occur in Shippingport. The fallout occurs as a clear liquid, but leaves a film upon drying.

Mist eliminator--Excessive mist carryover has occurred during scrubber operations. The mist eliminators were designed for 1 gr/scf liquid carryover, but plant personnel estimate actual carryover at 3 gr/scf. The horizontal mist eliminators installed as part of the vessels are also designed to operate at gas velocities of 8 to 10 ft/s. Pennsylvania Power is investigating installation of vertical mist eliminators in the ducting downstream of the scrubber vessels. Because of duct diameter and space restrictions, however, such an arrangement might generate flow velocities as high as 50 ft/s. A trial vertical mist eliminator was installed, but it collapsed as a result of structural failure caused by high flue gas velocity.

Water system--The system is not being operated in a closed loop as designed because water is being retained at the sludge disposal site and not recycled to the process. Makeup water from the disposal pond is not needed since fresh water is added to the system in the fan sprays and during lime slaking. Plant operators believe closed-loop operation is possible, but concentrated efforts to resolve the system's mechanical problems have allowed insufficient time to demonstrate this possibility. In the event they do not operate in a closed loop, the plant has a permit to discharge water to the Ohio River.

2.3.9.2 Cane Run No. 4, Louisville Gas and Electric--[4,5]

Introduction--The Cane Run Power Station, located in Louisville, Kentucky, is operated by the Louisville Gas and Electric Company (LG&E). The plant has six electric power steam generating units providing a total steam turbine net generating capacity of 992 MW.

Unit No. 4 is a coal-fired boiler with a continuous net generating capacity of 178 MW. Boiler and fuel data are presented in Table 2.3-13.

Table 2.3-13. BOILER AND FUEL DATA, CANE RUN NO. 4

Boiler capacity, MW (net)	178
Maximum generating capacity, MW	190
Unit heat rate, Btu/kWh	10,030
Sulfur content of coal, %	3.5 - 4.0 (avg.)
Ash content of coal, %	11 - 12 (avg.)
Heating value of coal, Btu/lb	11,500

The emission control system for this unit consists of an ESP in front of a wet scrubbing system. The ESP provides primary particulate control; the wet scrubber provides additional particulate removal and primary SO_2 control.

FGD system--The FGD system consists of two identical parallel scrubbing trains designed and installed by the American Air Filter (AAF) Company. The wet scrubbing system was put into operation in August 1976. The system uses calcium hydroxide sludge (carbide lime), a waste byproduct generated in a nearby acetylene plant. The system is guaranteed to remove 90 percent of the sulfur dioxide and 99 percent of the particulate matter from the flue gas.

The flow diagram (Figure 2.3-25) shows the FGD equipment and connecting mass flows.

Absorber--Because the FGD system was not providing the required SO_2 removal, LG&E and American Air Filter modified the unit to ensure its compliance with Federal and county standards.

As determined by LG&E tests, the following absorber modifications were made to achieve the required SO_2 removal:

- Increase of the L/G from 35 to 60.
- Reduction of pressure drop by adding turning vanes in the elbow and absorber base.
- Installation of additional spray headers above the mobile bed.
- Replacement of the existing spray nozzles with ceramic ones.

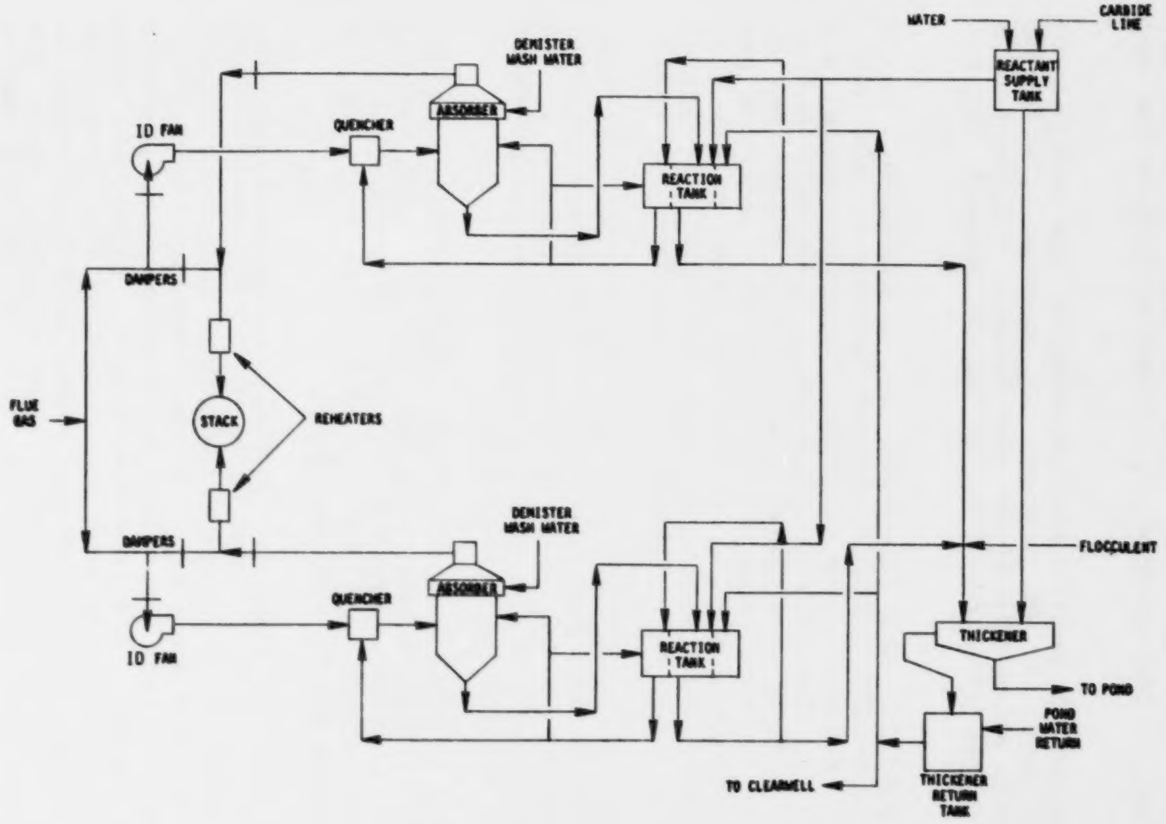

WATER
CARBIDE LIME
REACTANT SUPPLY TANK
DEMISTER WASH WATER
ID FAN
QUENCHER
ABSORBER
REACTION TANK
DAMPERS
FLUE GAS
STACK
REHEATERS
DEMISTER WASH WATER
DAMPERS
QUENCHER
ABSORBER
REACTION TANK
ID FAN
FLOCCULENT
THICKENER
TO POND
POND WATER RETURN
THICKENER RETURN TANK
TO CLEARWELL

Figure 2.3-25. Flow diagram of Can Run No. 4.

- Proposed addition of underbed sprays to help circulate the mobile bed balls.

The modules have three stages, with 1 ft of balls on each tray and 5 ft between stages. The 1-1/4-in.-diameter balls are made of polyurethane. The absorber is lined with Precrete and Placite 4005.

The above-mentioned modifications enabled the system to exceed the requirement for 85 percent SO_2 removal (Jefferson County) and to hold emissions below the Federal standard (1.2 $lb/10^6$ Btu). Test results indicated 86 to 89 percent SO_2 removal efficiency.

Quencher--Preceding each absorber is a quencher, which consists of a wetted-wall conical frustum section in the duct. Within the throat, several large-diameter injector nozzles are located tangential to the flow of flue gas, along with an internal spray header flow that parallels the gas stream in the center of the duct. These nozzles inject slurry into the gas stream to ensure thorough wetting of the flue gases before they enter the absorber. This minimizes possible scale formation caused by the dry flue gas reaching the absorber internals.

Reaction tank--The reaction tank is constructed of reinforced concrete and is divided into three compartments. Slurry flows from one compartment to the next through an opening in the bottom of the separating walls and, in emergencies, over weirs at the top of each compartment wall.

Reheat--Direct oil-fired heaters have been installed at the base of the stack in conjunction with the turning vanes to help correct the acid liquid carryover, which was attacking the stack. The reheat, which adds 40° to 50°F, will increase the exit flue gas temperature to 170° to 180°F.

ID fans--The booster fans are Buffalo Forge double-width, double-inlet units rated at 367,000 acfm at 325°F. The fans and fluid drive are powered by Reliance Electric induction motors rated at 1250 hp at approximately 720 rpm. Because these booster fans have insufficient capacity to overcome the pressure drop in the FGD system, the maximum boiler output has been limited to 150 to 155 MW. Certain modifications have been made to adjust the pressure drop. Turning vanes have been added in the flooded elbow area, at the base of the absorber, above the demister, and at the base of the stack. The radial vane demister has also been replaced by a chevron type. The booster fans are designed to handle a pressure drop of 13 in. H_2O through the FGD system.

Water removal and water system--Slurry is taken from the bottom of the reaction tank feed section and pumped to the 85-ft-diameter thickener, in which flocculant is added to aid settling. Sludge is removed from the bottom of the thickener and pumped to the pond. Liquid from the upper level flows into the thickener return tank and is pumped to the return section of the reaction tanks. Makeup water from the pond is added to the thickener return tank, and an emergency overflow is provided from the return tank to the pond.

2.3.9.3 Conesville No. 5, Columbus and Southern Ohio Electric Co.[6]--

Introduction--The Conesville Power Station is located on the Muskingum River near Coshocton in northeast Ohio. The plant has a present capacity of 1644 MW (design), and an addition with capacity of 411 MW is under construction. Units 1, 2, and 3 have a combined capacity of 433 MW and share a common stack. Unit 4 is rated at 800 MW, and Unit 5 at 411 MW. Unit 6, currently under construction, will also be rated at 411 MW. Units 4, 5, and 6 each have a separate stack.

Boiler 5 is a dry-bottom, pulverized-coal-fired Combustion Engineering unit, installed in 1976. Forty percent of the coal is delivered by conveyor from a coal mine complex 7 miles away. The remainder is hauled by truck from southeast Ohio. Boiler and fuel data are presented in Table 2.3-14.

FGD system--The system at Conesville No. 5 consists of a Research-Cottrell, cold-side ESP, followed by two Universal Oil Products (UOP) SO_2 absorber modules in parallel. The ESP is designed for 99.65 percent particulate removal, and the turbulent contact absorbers are designed for 89.6 percent SO_2 removal. The system is designed for an outlet SO_2 loading of 1.0 lb/million Btu of heat input. Boiler ID fans are located immediately downstream from the ESP.

Table 2.3-14. PERTINENT BOILER AND FUEL DATA FOR CONESVILLE NO. 5

Boiler capacity, MW (rated)	441
Plant capacity, MW (design)	1644
Boiler manufacturer	Combustion Engineering
Sulfur content of coal, %	4.2 to 5.1 (avg.)
Ash content of coal, %	12 to 19 (avg.)
Heating value of coal, Btu/lb	10,300 to 11,220

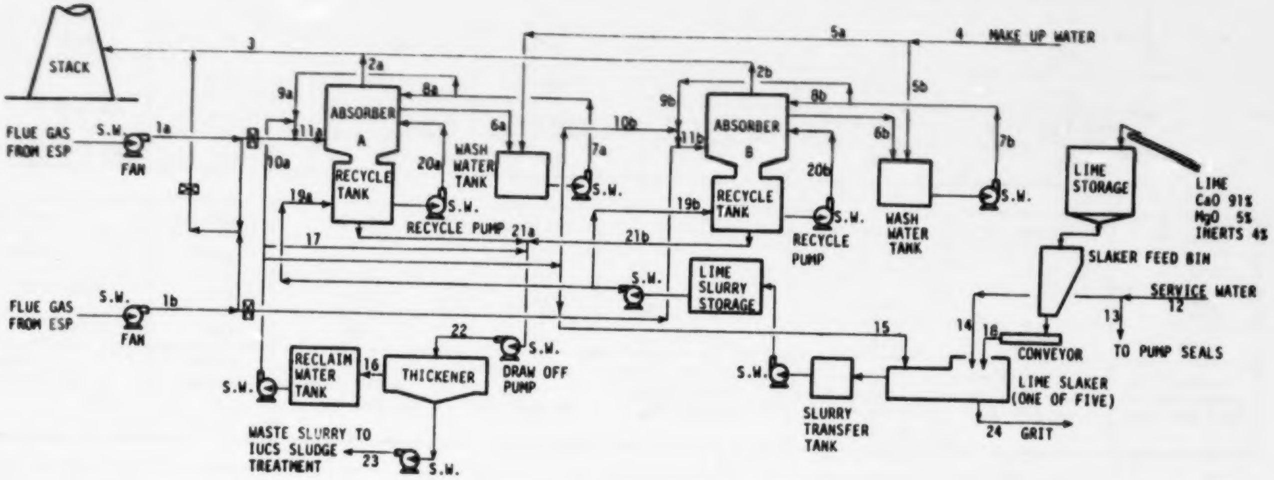
The flow diagram (Figure 2.3-26) shows the FGD equipment and connecting mass flows. The material balance for this plant is given in Table 2.3-15. The following paragraphs describe the system.

Absorber--Following the ID fans, the flue gas enters two parallel TCA absorbing trains. Each absorber is capable of handling 60 percent of the flue gas flow. A presaturator section, constructed of Carpenter 20, lowers the flue gas temperature from 286° to 125°F and provides some initial SO_2 removal. The gas then enters the neoprene-lined, carbon steel absorber modules, where two stages of 1.5-in. plastic balls provide a contacting surface for the lime slurry and the flue gas. The stages are approximately 5 ft apart. The lower stage is compartmented to maintain uniform ball depth. Following each absorber module, the flue gas passes through a fiberglass entrainment separator and two horizontal banks of chevron-type mist eliminator. The bottom of the trap-out tray is washed intermittently, and the lower mist eliminator is washed continually with recycled pond water. The flue gas from the parallel absorber trains then enters the 800-ft, Ceilcote-lined stack. Following the boiler ID fan, there is bypass breeching around the entire scrubber loop. Each module can be bypassed independently. No stack gas reheat is currently used, although it is possible that reheat will be added in the future.

FGD system tanks--Dravo thiosorbic lime from Maysville, Kentucky, is used in the UOP scrubber modules at a stoichiometric ratio of 1.1. The calcined, pelletized lime has a nominal particle diameter of 1.75 in., an MgO content of 3 to 8 percent, and a CaO content of 90 to 95 percent. The lime slaker discharges the slurry (20 percent solids) into an agitated lime slurry sump, where it is retained for 5 minutes before being pumped to the lime slurry storage tank, which handles surge requirements of the absorption system. Slurry is transferred from the storage tank to the TCA recycle tanks by variable-speed pumps, which respond to changing SO_2 concentrations and boiler loads by means of a pH monitor. The scrubbing liquor contains about 7 to 12 percent solids and is recirculated by four pumps (one standby), each rated at 12,000 gal/min. The pH at the scrubber outlet is 5.8, and pH in the recycle tank is approximately 6.8.

A bleed stream of spent reaction products is withdrawn continuously from the recycle tank and pumped to the thickener system.

Wash water tanks supply the presaturator and demister. Information regarding the FGD tanks is given in Table 2.3-16.


STACK
FLUE GAS FROM ESP
S.W.
FAN
1a
FLUE GAS FROM ESP
S.W.
FAN
1b
3
2a
9a
8a
11a
10a
ABSORBER A
RECYCLE TANK
19a
20a
S.W.
RECYCLE PUMP
17
21a
6a
WASH WATER TANK
7a
S.W.
5a
4
MAKE UP WATER
5b
2b
9b
8b
10b
11b
ABSORBER B
RECYCLE TANK
19b
20b
S.W.
RECYCLE PUMP
21b
6b
WASH WATER TANK
7b
S.W.
S.W.
LIME SLURRY STORAGE
22
S.W.
DRAW OFF PUMP
S.W.
RECLAIM WATER TANK
16
THICKENER
WASTE SLURRY TO IUCS SLUDGE TREATMENT
23
S.W.
LIME STORAGE
LIME
CaO 91%
MgO 5%
INERTS 4%
SLAKER FEED BIN
SERVICE WATER
12
13
TO PUMP SEALS
15
14
18
CONVEYOR
LIME SLAKER (ONE OF FIVE)
24
GRIT
S.W.
SLURRY TRANSFER TANK

Note: S.W. SEAL WATER INPUT TO PUMPS

Figure 2.3-26. Flow diagram of Conesville No. 5.

Table 2.3-15. MATERIAL BALANCE FOR CONESVILLE NO. 5

Description (Gas)	1 Total gas for cleaning	1a and 1b Gas for scrubber A, B	2a and 2b Gas from scrubber A, B	3 Flue gas at outlet battery limit
Mass flow rate 10^3 lb/h	4,440	2,220	2,280	4,560
acfm 10^3	1,394	697	583	1,166
Temp., °C (°F)	147 (296)	147 (296)	52 (126)	52 (126)
Gauge press. (in. H_2O)	8.0	8.0	0.8	0.8
Fly ash, 10^3 lb/h	.194	.097	.077	.154
SO_2 10^3, lb/h	39	19.5	2	4
CO_2, N_2, O_2 10^3 lb/h	4,160	2,080	2,078	4,156
H_2O 10^3 lb/h	240	120	200	400

Description (Water)		4 Makeup water	5a and 5b Makeup water to Wash Tank A, B	6a and 6b Return wash water	7a and 7b Wash water pump discharged	8a and 8b Demister and wash water to Scrubber A, B	9a and 9b Makeup water to presat.	10a and 10b Return water to presat.	11a and 11b Total water to presat.	12 Service water to system	13 Service water to pump seals	14 Service water to slakers	15 Return water to slaker	16 Return water from thickener	17 Return water to draw-off pump
Mass flow rate	10^3 lb/h	187	93.5	500	597.5	545	52.5	82.5	135	158.5	64.5	94	158.3	394.5	75
	gal/min	374	187	1000	1,195	1,090	105	165	270	317	129	188	317	789	150
Specific gravity		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Temp., °C (°F)		27 (80)	27 (80)	52 (126)	52 (125)	52 (125)	52 (125)	38 (100)	33 (100)	amb	amb	amb	38 (100)	38 (100)	38 (100)

(continued)

Table 2.3-15 (continued)

Description (Slurry)		18 Lime to system	19a and 19b Slurry to Recycle Tank A, B	20a and 20b Recycle slurry to Scrubber A, B	21a and 21b Spent slurry to draw-off pond	22 Thickener feed slurry	23 Waste sludge for disposal	24 Grit
Mass flow rate	10^3 lb/h	34.1	143.2	20,540	281.4	641.8	251.3	4.2
	gal/min	-	261	38,000	521	1200	420	-
Solids, %		-	14.76	13	13	11.57	29.5	-
$CaSO_3 \cdot 1/2\ H_2O$, 10^3 lb/h		-	-	1,926	26	52.8	52.8	-
$CaSO_4 \cdot 2\ H_2O$, 10^3 lb/h		-	-	642	9	17.6	17.6	-
$MgSO_4$, 10^3 lb/h		-	1.7	423	6	13	5	-
Specific gravity		-	1.1	1.08	1.08	1.08	1.22	-
Temp., °C (°F)		-	amb	52 (126)	52 (126)	52 (126)	38 (100)	-

Note: amb = ambient

Table 2.3-16. FGD TANK INFORMATION FOR CONESVILLE NO. 5.

Item	Slurry transfer tank	Slurry storage tank	Recycle tank	Wash water tank
Unit size	16 ft dia., 10 ft high	20 ft dia., 22 ft high	45 ft dia., 28 ft high	8 ft dia., 10 ft high
Capacity	15,825 gal	51,700 gal	332,930 gal	3,600 gal
Material of construction	Fiberglass (FRP)	Carbon steel	Carbon steel	Fiberglass (FRP) steel shell

Waste system--The thickener is 100 ft in diameter and 14 ft deep in the center. The reaction product slurry is fed continuously from the recycle tanks and concentrated to an underflow composition of approximately 40 percent solids. This underflow is cycled to IU Conversion Systems, Inc., (IUCS) fixation facilities, where it is further thickened, vacuum-filtered, and mixed with a blend of dry fly ash and lime to form a 73 percent solid substance (IUCS Poz-o-tec). The product is currently being discharged to a 3500-acre-foot diked pond.

The wastewater pond received ash sluice water, cooling water blowdown, and water from the sludge treatment plant. This system is not operating in the closed-loop mode at present.

2.3.9.4 Green River Station, Kentucky Utilities[7,8]--

Introduction--The Green River Station of Kentucky Utilities (KU) is located on the Green River in Central Kentucky, approximately 5 miles north of Central City. American Air Filter (AAF) designed and installed a tail-end wet lime scrubbing system on Boilers 1, 2, and 3. These boilers service two turbines rated at 32 MW (gross) each. The station operates a total of four steam turbines with a combined generating capacity of 242 MW. All three boilers are dry-bottom, pulverized-coal-fired units manufactured by Babcock and Wilcox, and were installed in 1949 and 1950. They are used for peak loads and are normally operated 5 days a week, with one or more of the boilers often at reduced load. Present plans do not call for retirement of these units.

Heat rate is approximately 13,250 Btu/net kWh per unit. The boilers burn primarily a high-sulfur western Kentucky coal that has an average heating value of 10,800 Btu/lb, a sulfur content of 3.8 to 4.0 percent, and an ash content of 13 to 14 percent. Boiler and fuel data are presented in Tables 2.3-17 and 2.3-18.

FGD system--The FGD system at Green River was started up on a half-load basis in September 1975. It continued to operate at half load until March 1976, when operation began at full-load capacity in a closed-water-loop mode. The FGD system uses slaked lime for primary SO_2 removal. Sulfur dioxide removal efficiency usually averages more than 90 percent, well above the guaranteed design efficiency (80%).

Primary particulate removal is provided by Western Precipitator multicyclones designed to operate at an efficiency of 85 percent. A variable-throat venturi scrubber designed to operate at an overall efficiency of 99.7 percent provides additional particulate removal. Under full-load conditions, the maximum

Table 2.3-17. PERTINENT BOILER DATA, GREEN RIVER PLANT

Boiler data	Item
Boiler	Nos. 1, 2, and 3
Boiler manufacturer	Babcock and Wilcox
Year placed in service	1949, 1950
Total generating capacity	64 MW
Maximum heat input	848 10^6 Btu/h
Heat rate per unit	13,250 Btu/net kWh
Percent excess air required	25
Percent boiler efficiency	80

Table 2.3-18. FUEL DATA, GREEN RIVER PLANT

Fuel data	
Type (primary)	High-sulfur western Kentucky coal
Analysis	3.9 percent sulfur
	13.4 percent ash
	12.1 percent total moisture
Heating value	10,800 Btu/lb
Fuel consumption	1,416 10^6 short tons/wk

allowable particulate and sulfur dioxide emissions are 0.097 lb/10^6 Btu and 1.67 lb/10^6 Btu of heat input, respectively. Actual emissions are unknown at this time because air leakage in the boilers has caused monitoring to be indecisive. The flow diagram in Figure 2.3-27 shows FGD equipment and connecting mass flows on Green River Boilers 1, 2, and 3. The following paragraphs describe the system.

Scrubber train--Flue gas desulfurization and particulate removal systems are combined in a single scrubber module designed to handle a maximum of 360,000 acfm of flue gas at 300°F. This scrubber module contains a mobile bed contactor for SO_2 removal and a variable-throat, flooded-elbow venturi for fly ash removal.

The absorber is 20 by 20 ft, and 22.5 ft high, and is constructed of mild steel with a 3/4-in.-thick, acid proof Precrete lining. The internals consist of a mobile bed with 10 compartments. The mobile bed stage contains approximately 175,000 to 190,000 solid 1.25-in.-diameter balls, packed to a maximum thickness of 2 ft (16 in. at rest). The balls are made of polyvinyl chloride and polyethylene. Underbed dampers are used to adjust for reduced removal requirements during periods of low steam demand.

The variable-throat venturi scrubber is constructed of mild steel with a stainless steel throat and acidproof brick lining. It has a 100-in. throat opening with a 94-in. plug.

The original mist eliminator of stainless steel construction is a single-stage, spin-vane type positioned 27.5 ft above the scrubber bed. The mist eliminator depth and vane spacing are 3 ft. Gas flows through the demister first horizontally, then vertically; pressure drop is 2 in. H_2O. Kentucky Utilities is attempting to optimize the operation of the mist eliminator. If they fail, they intend to replace it with a standard design, chevron-type mist eliminator.

Data regarding the scrubber are presented in Table 2.3-19.

FGD system tanks--The FGD system has a slaker tank, a mix/hold tank, and a reaction tank.

A storage bin equipped with a vibrating bottom and an 8-in. screw conveyor discharges lime at a rate of 2 tons/h into the covered, agitated slaking tank. Two agitated slake tanks were installed for this purpose, one serving as a backup. Each has a liquid volume capacity of 1680 gal, and each is equpped with a 10-hp, 84-rpm agitator.

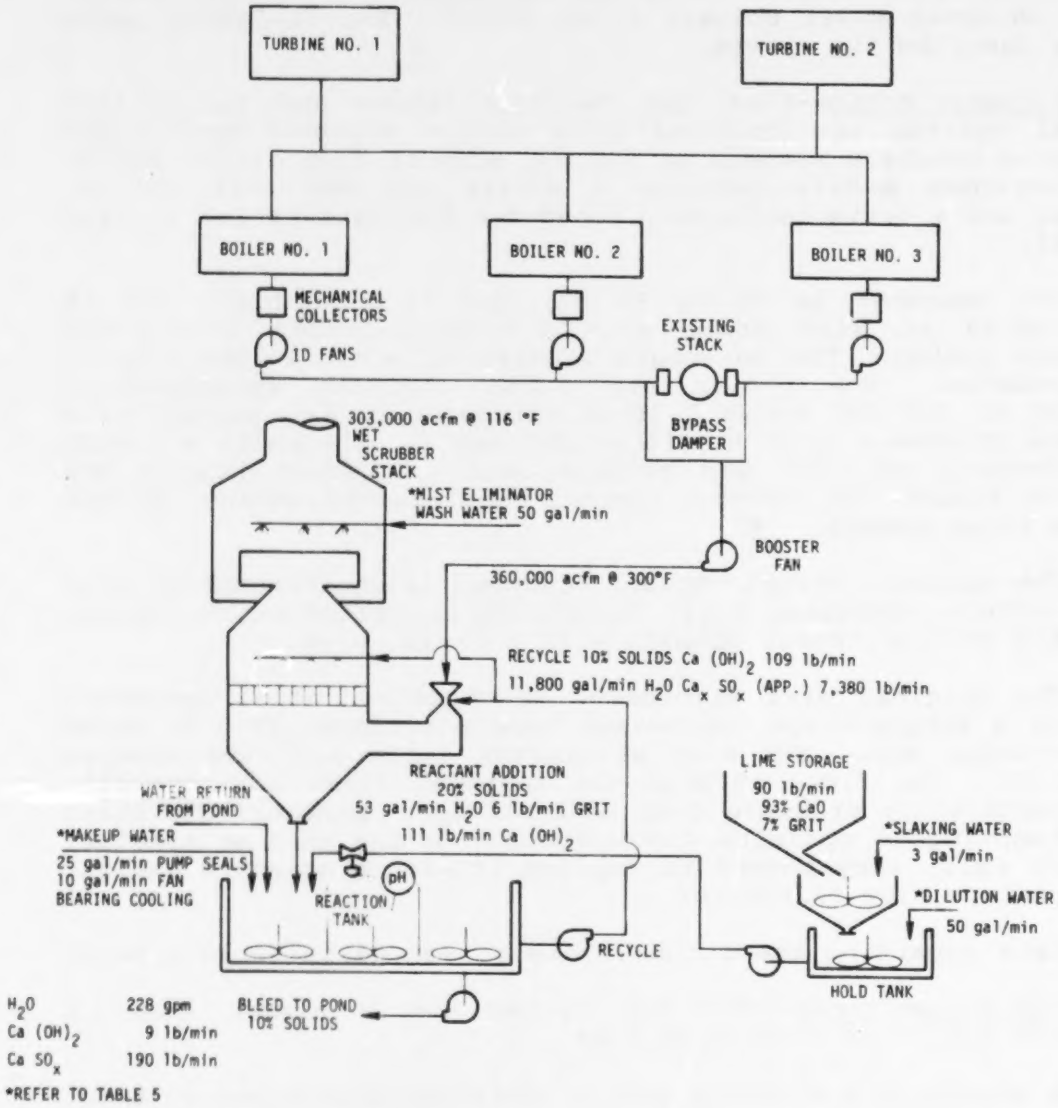

TURBINE NO. 1
TURBINE NO. 2
BOILER NO. 1
BOILER NO. 2
BOILER NO. 3
MECHANICAL COLLECTORS
ID FANS
EXISTING STACK
BYPASS DAMPER
303,000 acfm @ 116 °F
WET SCRUBBER STACK
*MIST ELIMINATOR WASH WATER 50 gal/min
BOOSTER FAN
360,000 acfm @ 300°F
RECYCLE 10% SOLIDS Ca (OH)$_2$ 109 lb/min
11,800 gal/min H$_2$O Ca$_x$ SO$_x$ (APP.) 7,380 lb/min
REACTANT ADDITION
20% SOLIDS
53 gal/min H$_2$O 6 lb/min GRIT
111 lb/min Ca (OH)$_2$
WATER RETURN FROM POND
*MAKEUP WATER
25 gal/min PUMP SEALS
10 gal/min FAN BEARING COOLING
pH
REACTION TANK
RECYCLE
LIME STORAGE
90 lb/min
93% CaO
7% GRIT
*SLAKING WATER
3 gal/min
*DILUTION WATER
50 gal/min
HOLD TANK
BLEED TO POND
10% SOLIDS
H$_2$O 228 gpm
Ca (OH)$_2$ 9 lb/min
Ca SO$_x$ 190 lb/min
*REFER TO TABLE 5

Figure 2.3-27. Flow diagram of Green River Station.

Table 2.3-19. GREEN RIVER SCRUBBER DATA

Data	Item
Particulate scrubber	
Type	Variable throat venturi at flooded elbow
Manufacturer	American Air Filter
Scrubber pressure drop (in. H_2O)	7
Dimensions	Throat 8 ft 4 in., plug, 7 ft 10 in.
Material of construction	
Shell	Mild steel with stainless steel throat
Shell lining	Acidproof Precrete
No. of stages	1
Nozzle size	1.5-in. orifice, 1360 gal/min in venturi, 690 gal/min in damper
No. of nozzles	12
SO_2 absorber	
Type	Mobile bed contactor
Manufacturer	American Air Filter
L/G ratio, gal/1000 ft^3	39.5
Absorber pressure drop (in. H_2O)	4
Dimensions	20 by 20 ft, and 27.5 ft high
Material of construction	
Shell	Mild steel
Shell lining	0.25-in. acidproof Precrete
Internals	
Type	Mobile bed (ping-pong balls)
No. of stages	1 (10 compartments)
Packing thickness	1.33 ft at rest, 20 ft in use

Slurry is discharged from the slaker to a mix/hold tank. This tank, which has a liquid volume capacity of 1980 gal, is also agitated (5-hp, 45-rpm agitator). The fresh scrubbing slurry (20 percent solids) is then pumped to the return section of the reaction tank installed beneath the scrubbing module.

The reaction tank, constructed of acidproof concrete, is 72 by 24 ft, and 24 ft high. Two partitions form three individual compartments, each agitated and connected by underflow openings. The total liquid capacity of each compartment is 100,000 gal. Total retention time in the reaction tank is 21 min (7 min per compartment). The function of each compartment is descibed below:

- The return section of the reaction tank system receives the reaction products and collected fly ash discharged from the scrubbing module. Fresh lime slurry, fresh makeup water (cleaned river water), and pond return water are also supplied to the system at this point.
- The recycle/discharge section of the reaction tank feeds both the venturi scrubber and the mobile bed contactor with recycled scrubbing solution. Bleed pumps remove the scrubbing wastes from this section of the reaction tank so that a 10 percent solids slurry will be maintained in the tank. The bleed stream is discharged to a settling pond, and clear water is returned from the pond to the return section of the reaction tank.
- One additional section, situated between the return and recycle sections of the reaction tank, was installed only for the purpose of providing additional checks on the process chemistry.

Table 2.3-20 summarizes reaction tank data.

Table 2.3-20. REACTION TANK DATA, GREEN RIVER PLANT

Data	Item
Materials of construction	Acidproof concrete
Configuration/dimensions	Rectangular - 3 compartments 24 by 24 ft, and 24 ft high
Capacity, gal	103,680 per compartment
Retention time	7 min per compartment; 21 min total
Covered	No
Agitators	1 agitator per compartment
Materials of construction	Rubber-lined agitator
Horsepower	50 hp, 45 rpm, 84-in.-dia. turbine agitator

Disposal and water system--Reaction products and collected particulate matter are pumped to an impervious, clay-lined pond located on the plant site approximately 0.8 mile from the scrubbing module. The pond capacity is 148 acre-ft at a depth of 20 ft. Calculated life expectancy of this pond is approximately 9 years, but it is expandable to 414 acre-ft, which would yield another 20 years. The closed-loop operation returns clarified pond water to the reaction tank. Treated river water is used as makeup and is introduced into the reaction tank, lime slaking tank, and demister, as well as the various pump seals and fan bearings. The makeup water requirements are listed in Table 2.3-21.

Table 2.3-21. MAKEUP WATER REQUIREMENTS, GREEN RIVER PLANT (gallons/minute)

Lime slaking	
Slaker	3
Mix/hold tank	50
Pump seals	25
Fan bearing cooling	10
Demister wash water	50
Total	138

2.3.9.5 Paddy's Run Station, Louisville Gas and Electric[9,10]--

Introduction--The Paddy's Run Station of Louisville Gas and Electric Company (LG&E) is used primarily to meet peak loads. This station has six generators, but only the boiler on Unit 6 is retrofitted with an FGD system. This dry-bottom, pulverized-coal-fired boiler was installed by Foster-Wheeler in 1951. It is rated at 65 MW, but runs at 71 to 72 MW at full load. The heat rate ranges from 13,000 to 13,500 Btu/kWh. The boiler burns Peabody high-sulfur coal, which has an average heating value of 12,400 Btu/lb, ash content of 15 percent, and a sulfur content of 3.7 percent. Boiler and fuel data are presented in Tables 2.3-22 and 2.3-23.

FGD system--The FGD system, a lime scrubber designed by Combustion Engineering, Inc., was put into operation in April 1973. The system uses calcium hydroxide sludge (carbide lime), a waste byproduct generated in a nearby acetylene plant. The slurried mixture of this carbide lime constitutes the replenishing fresh scrubbing slurry. The system meets the required >85 percent SO_2 removal efficiency, and sometimes operates at efficiencies greater than 99 percent.

A Research-Cottrell ESP, which operates at 99 percent efficiency, provides primary particulate removal and keeps the boiler in compliance with the maximum allowable rate of 0.1 lb/10^6 Btu of heat input. Continuous monitoring equipment shows that Unit 6 is also in compliance with regulations limiting atmospheric emission of SO_2 to 1.2 lb/10^6 Btu of heat input.

The flow diagram in Figure 2.3-28 shows Unit 7 FGD equipment and connecting mass flows. The following paragraphs describe the system.

Absorber--The FGD system consists of two identical absorber modules, each sized to handle 175,000 acfm at 350°F. The absorbers are constructed of a mild steel coating with a fiberglass reinforced polyester (FRP) flake lining 1/2 in. thick. Internal supports are Type 316 stainless steel. Each absorber contains two beds of 1-in. glass marbles. The packing thickness of each bed is 3 in. The thickness of the layer is controlled by the neight of the overflow pots.

Atop the absorbers are two-stage chevron mist eliminators followed by gas reheaters. The modules are 17 by 18 ft, and 50 ft high. Table 2.3-24 presents additional absorber data.

FGD systems tanks--The FGD system has an additive slurry tank, a reaction tank, and a reaction surge tank. All three are constructed of mild steel.

Table 2.3-22. BOILER DATA FOR UNIT 6, PADDY'S RUN STATION

Boiler data	Item
Boiler manufacturer	Foster-Wheeler
Year placed in service	1951
Unit rating	65 MW (nameplate), 70 MW (maximum continuous, net)
Unit rating at full load	71 to 72 MW
Maximum heat input	910 million Btu/h
Maximum continuous heat input	810 million Btu/h
Maximum flue gas rate	400,000 acfm at 325°F
Percent excess air required	25 to 30
Heat rate	13,000 to 13,500 Btu/kWh

Table 2.3-23. FUEL DATA FOR UNIT 6, PADDY'S RUN STATION

Fuel data	Item
Type	Peabody high sulfur coal
Analysis	14 percent ash, 3.7 percent sulfur
Heating value, Btu/lb	12,400
Fuel consumption at maximum heat input, lb/h	73,400
Fuel consumption at maximum continuous heat input, lb/h	65,300

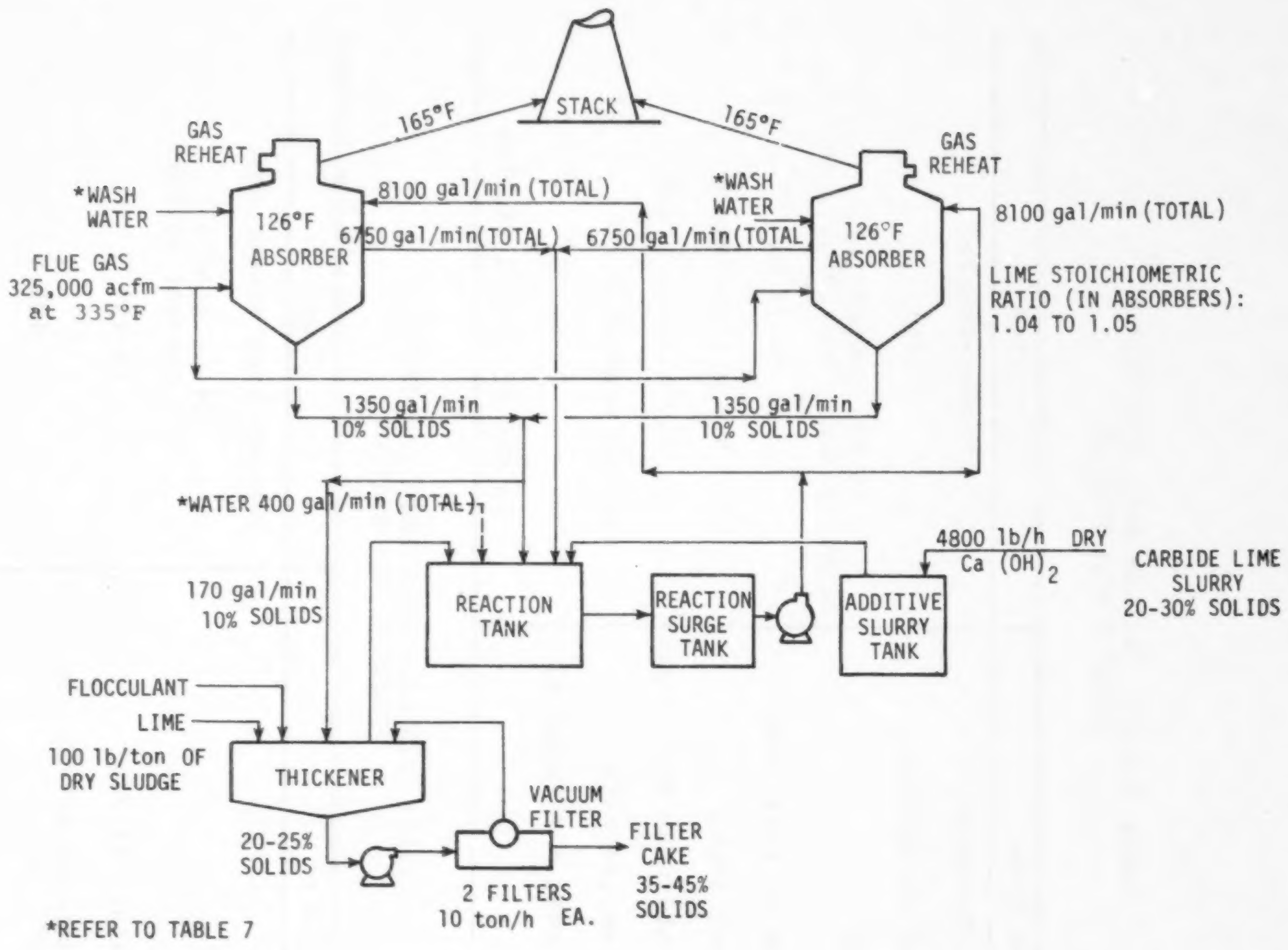

STACK
165°F
165°F
GAS REHEAT
GAS REHEAT
*WASH WATER
*WASH WATER
FLUE GAS 325,000 acfm at 335°F
126°F ABSORBER
126°F ABSORBER
8100 gal/min (TOTAL)
8100 gal/min (TOTAL)
6750 gal/min (TOTAL)
6750 gal/min (TOTAL)
LIME STOICHIOMETRIC RATIO (IN ABSORBERS): 1.04 TO 1.05
1350 gal/min 10% SOLIDS
1350 gal/min 10% SOLIDS
*WATER 400 gal/min (TOTAL)
170 gal/min 10% SOLIDS
REACTION TANK
REACTION SURGE TANK
ADDITIVE SLURRY TANK
4800 lb/h DRY Ca (OH)2
CARBIDE LIME SLURRY 20-30% SOLIDS
FLOCCULANT
LIME
100 lb/ton OF DRY SLUDGE
THICKENER
20-25% SOLIDS
VACUUM FILTER
2 FILTERS 10 ton/h EA.
FILTER CAKE 35-45% SOLIDS
*REFER TO TABLE 7

Figure 2.3-28. Flow diagram of Paddy's Run.

Table 2.3-24. ABSORBER DATA, PADDY'S RUN

Data	Item
Type	Tower
L/G ratio, gal/1000 ft^3 at 126°F	15 to 18/stage
Gas velocity through absorber, ft/s	8 to 12
Material of construction	
Shell	Mild steel with an FRP flake lining 2-1/2 in. thick
Internals	316 stainless
Internals	
Type	Marble bed
Number of stages	2
Type and size of packing	Glass marbles - 1 in.
Packing thickness per stage	3 in.
Material of construction	
Packing Supports	Glass 316 stainless
Absorber train pressure drop	
ΔP across each marble bed (in. H_2O)	5.5 to 6
ΔP across tower (in. H_2O)	11 to 12
ΔP across demister (in. H_2O)	1.5
ΔP due to ductwork (in. H_2O)	3 to 4
Total ΔP (in. H_2O)	15 to 18

Stockpiled carbide lime is diluted from a 50 percent solids mixture to a 20 to 30 percent solids mixture before it is fed to the additive slurry tank, which serves as a holding tank. During full-load operations, surge capacity is 2-1/2 hours.

"Black lime," a byproduct from the lime kiln scrubber of an acetylene plant, is added to the carbide lime in the additive slurry tank. The analysis of black lime is essentially the same as that of carbide lime, except that the magnesium oxide (MgO) content is higher (2 to 4 percent) and the lime contains less $Ca(OH)_2$ and more $CaCO_3$. The carbide lime analysis is presented in Table 2.3-25.

Table 2.3-25. CARBIDE LIME ANALYSIS, PADDY'S RUN (percent)

Solids analysis	
$Ca(OH)_2$	90-92
$CaCO_3$	3-8
SiO_2	2-2.5
C	0.3
S	0.03
MgO	<0.1
Cl	trace

Mass flows of carbide lime slurry from the additive tank, slurry from absorber, water from the thickener, filtrate from the vacuum filter, and makeup water are fed into the reaction tank, where they are mixed by mechanical agitators. Under full-load conditions, the mixture is retained for 20 minutes before it is pumped to the reaction surge tank. The slurry is retained 3 minutes in the reaction surge tank, then sent to the absorber spray nozzles. The location of the reaction surge tank downstream from the reaction tank ensures proper mixing and precipitation of scale before the slurry is used in the absorbers. Table 2.3-26 presents FGD tank data.

Thickener--Slurry bled from the absorber into the thickener has a solids content of 9.5 to 10.5 percent. Lime is added at this point to stabilize the sludge. The lime consumed for this purpose amounts to about 100 lb/ton of dry sludge solids generated. Flocculant is injected into the thickener to aid settling

Table 2.3-26. FGD TANK DATA, PADDY'S RUN

Item	Additive slurry tank	Reaction surge tank	Reaction tank
Size and capacity	8 ft dia., 17 ft high (6,400 gal)	20 ft dia., 15 ft high (35,200 gal)	48 ft dia., 17 ft high (210,000 gal)
Retention time at full load	2-1/2 h	3 min	20 min
Solids concentration, %	20 to 30	10	10
Material of construction	Mild steel	Mild steel	Mild steel

Table 2.3-27. THICKENER AND VACUUM FILTER DATA, PADDY'S RUN

Thickener	
Number	1
Dimensions and capacity	50 ft dia., 14 ft high (205,500 gal)
Solids concentration, %	10 in 20-24 out
Retention time at full load	4.3 h
Material of construction	Mild steel
Rotary vacuum filter	
Number	2
Cloth area/filter	150 ft^2/filter
Capacity	10 tons/h (wet cake)
Solids concentration, %	20-24 in 35-45 out
Precoat	none

by maintaining a concentration of 4 to 7 ppm. Mass flows from the thickener consist of underflow effluent (which has a solids content of 20 to 25 percent) to the vacuum filter, and weir overflow water to the reaction tank. Table 2.3-27 presents data regarding the thickener and the vacuum filter.

Vacuum filter--Underflow from the thickener is sent to two rotary vacuum filters, each with a wet-cake capacity of 10 tons/h. The filters produce a filter cake with a solids content of 35 to 45 percent. The cake is trucked to an offsite landfill. The filtered weir water is returned to the thickener for reuse.

Liquid system--The liquid system operates in a closed-loop mode. About 40 gal of makeup water is added per lb-mol of SO_2 removed. The FGD system required 400 gal/min of freshwater (river). Table 2.3-28 lists the water requirements.

Table 2.3-28. WATER REQUIREMENT, PADDY'S RUN
(gallons per minute)

Dilution of carbide lime feed to additive tank, reaction tank water feed, and replenish losses via stack gas and filter cake	350
Demister wash water	5
Pump seals	30-40
Other	5
Total	390-400

2.3.9.6 Phillips Power Station, Duquesne Light Co.[11,12,13,14]--

Introduction--The Phillips Power Station of the Duquesne Light Company is located on the Ohio River in Allegheny County, Pennsylvania, 20 miles northwest of Pittsburgh. The plant consists of six generating units having a total gross continuous generating capacity of 408 MW. The net station capacity is 373 MW when all four scrubber modules and the absorber module are operating. All the generators are cycling, base-load units. Unit No. 6 is the largest generator, having a net capacity of 143 MW. All the boilers, manufactured by Foster-Wheeler, are dry-bottom, pulverized-coal-fired units. The first unit was installed in 1942, and the sixth unit in 1956.

Coal burned at the station, as received, has an average gross heating value of 11,350 Btu/lb. Ash content, on a dry basis, is 18.2 percent, and sulfur content is 2.15 percent. Boiler data are tabulated in Table 2.3-29.

Table 2.3-29. BOILER DATA, PHILLIPS POWER STATION

Boiler data	Item
Boiler capacity, MW (gross)	
Units 1,2	35
3,4,5	65
6	148
Boiler manufacturer	Foster-Wheeler
Years placed in service	1942-1956
Maximum continuous generating capacity, MW (net)	373
Maximum heat input, 10^6 Btu/h	4,463
Heat rate, Btu/kWh (net)	11,900
Maximum flue gas rate, acfm at 360°F	1,650,000

FGD system--The lime FGD system at the Phillips Power Station was the first in the United States. The Phillips scrubber system began operation in July 1973. Primary particulate emission control is provided by mechanical collectors followed by an ESP on each boiler. Downstream, final particulate control is achieved by four parallel Chemico venturi scrubbers with design efficiencies of 99 percent. These scrubbers also remove approximately 50 percent of the SO_2 entering the system. Emissions of SO_2 from one scrubber are further controlled by a Chemico second-stage venturi absorber, with lime as the absorbent. Performance guarantee tests indicate that the SO_2 removal efficiency of this two-stage train has averaged about 90 percent. The system's overall SO_2 removal efficiency is 50 to 60 percent.

The maximum particulate emission is limited to 0.08 lb/10^6 Btu of heat input. Particulate emissions from the unit are in compliance with that regulation.

Atmospheric emissions of SO_2 are limited to 0.6 lb/10^6 Btu of heat input. Present SO_2 emissions from the single-stage scrubbing system, using high-calcium lime, exceed this limit. Bringing the system into compliance will require an SO_2 removal efficiency of 83 percent.

Extensive tests conducted from October through December 1975 showed that the necessary SO_2 removal could be achieved with the existing single-stage scrubber trains by using thiosorbic lime. Although original plans were to achieve compliance with dual-stage scrubbers, Duquesne Light has notified the regulatory agencies that it will operate the existing single-stage scrubbing system with Dravo's Thiosorbic lime.

The flow diagram in Figure 2.3-29 shows FGD equipment and connecting mass flows of the dual-stage scrubber train. The following paragraph describes the system.

Scrubber train--All four scrubber trains are equipped with Chemico variable-throat venturi scrubbers for removal of fly ash and SO_2. The fourth train has an added second venturi for increased SO_2 absorption. The system was designed to handle a total gas volume of 2,190,000 acfm with all four trains in service. The cleaned gases exiting the trains enter a common wet duct (also lined with Ceilcote) that leads to a 340-ft, acid-resistant, brick-lined, concrete stack. A 316L stainless steel section of the duct preceding the stack is equipped with a direct oil-fired reheater unit that can raise stack gas temperature in the range of 110° to 120°F by as much as 30°F. Normal reheat is about 20°F. Information regarding the scrubbers is given in Table 2.3-30.

Table 2.3-30. PHILLIPS POWER SCRUBBER DATA FOR PARTICULATE AND FGD SCRUBBER MODULES

Superficial gas velocity, ft/s	40
Module size	40 ft dia., 50 ft high
Equipment internals	Venturi
Material of construction	
Shell	Mild steel, Ceilcote liner
Internals	Some 316L stainless, Ceilcote liner

ID fans--Gases leaving the scrubbers enter booster ID fans equipped with freshwater sprays to remove any accumulation of solids resulting from scrubber carryover. The ID fan housings are lined with 1/4-in. thick natural rubber. Wheel material is Carpenter 20 Cb 3, a stainless steel containing niobium and tantalum. The fan shaft is 316L stainless steel. The spray nozzles have been relocated and replaced by a new type (Bete fog nozzle No. TF16FC), and a Neoprene-29 rubber coating has been applied to the 316L SS fan hubs. Each fan is driven by a 5500-hp motor. A closed system supplies cooling water to the fan bearings.

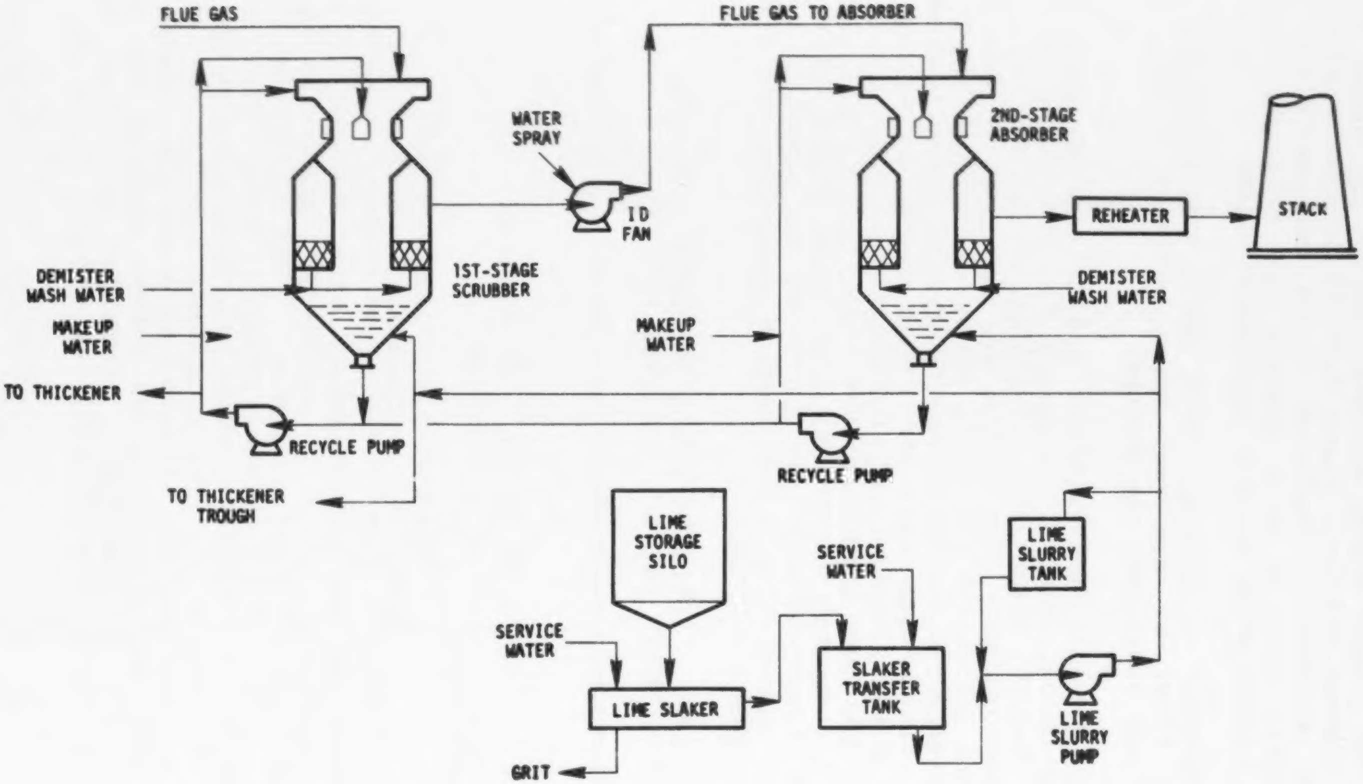

FLUE GAS
FLUE GAS TO ABSORBER
WATER SPRAY
ID FAN
2ND-STAGE ABSORBER
REHEATER
STACK
DEMISTER WASH WATER
1ST-STAGE SCRUBBER
MAKEUP WATER
TO THICKENER
RECYCLE PUMP
TO THICKENER TROUGH
MAKEUP WATER
DEMISTER WASH WATER
RECYCLE PUMP
LIME STORAGE SILO
SERVICE WATER
LIME SLAKER
GRIT
SERVICE WATER
SLAKER TRANSFER TANK
LIME SLURRY TANK
LIME SLURRY PUMP

Figure 2.3-29. Flow diagram of the dual-stage scrubber train at Phillips. The complete scrubbing system includes four trains, three have first stages with mist eliminators instead of second stages.

Sludge disposal--Phillips Power Station will be using a new sludge disposal system. I.U. Conversion Systems (IUCS) was awarded a new, long-term waste management contract. The Poz-O-Tec system uses vacuum filtration to dewater the thickener underflow followed by agitated addition of dry ash and an IUCS additive. Compaction of the final product will occur at the nearby Duquesne Light Company landfill area.

Service water--A service (river) water system, independent of the power station service water system, includes a pair of 900-gal/min, 100-hp pumps taking suction from the existing condenser discharge tunnel and a 10-in. distribution header for the scrubber facility. It provides water for the fan spray, pump seal, demister spray, instrumentation flush, reagent mixing tank, and the emergency water supply for the scrubbers.

2.3.10 Conversion Factors

This section provides tables to aid in converting the numbers in this report to any appropriate system of units. These factors are given in Table 2.3-31.

Table 2.3-31. CONVERSION FACTORS

Multiply	By	To obtain
Atmospheres (atm)	76.0	cm Hg
	29.92	in. Hg
	33.90	ft H_2O
	1.0333	kg/cm^2
	14.70	$lb/in.^2$
	1.013	bars
Barrel - oil (bbl)	42	gal - oil
British thermal units (Btu)	0.2520	kg - cal
	777.5	ft - lb
	3.927×10^{-4}	hph
	107.5	kg - m
	2.928×10^{-4}	kWh
Btu/minute (Btu/min)	12.96	ft - lb/s
	0.02356	hp
	0.01757	kW
	17.57	W
Centimeters of mercury (cm Hg)	0.01316	atm
	0.4461	ft H_2O
	136.0	kg/m^2
	27.85	lb/ft^2
	0.1934	$lb/in.^2$
Cubic centimeters (cm^3)	3.531×10^{-5}	ft^3
	6.102×10^{-2}	$in.^3$
	1.308×10^{-6}	yd^3
	2.642×10^{-4}	gal

(continued)

Table 2.3-31. (continued)

Multiply	By	To obtain
Cubic feet (ft^3)	2.832×10^4	cm^3
	1728	$in.^3$
	0.02832	m^3
	0.03704	yd^3
	7.48052	gal
	28.32	liters
Cubic feet/minute (ft^3/min)	472.0	cm^3/s
	0.1247	gal/s
	0.4720	liters/s
	62.4	lb H_2O/min
Cubic feet/second (ft^3/s)	0.646317	million gal/day
	448.831	gal/min
Cubic meters (m^3)	35.31	ft^3
	61.023	$in.^3$
	1.308	yd^3
	264.2	gal
Feet (ft)	30.48	cm
	0.3048	m
Feet of water (ft H_2O)	0.02950	atm H_2O
	0.8826	in. H_2O
	0.03048	kg/cm^2
	62.43	lb/ft^2
	0.4335	$lb/in.^2$
Foot-pounds (ft-lb)	1.286×10^{-3}	Btu
	5.050×10^{-7}	hph

(continued)

Table 2.3-31. (continued)

Multiply	By	To obtain
Foot-pounds	3.241×10^{-4}	kg - cal
	0.1383	kgm
	3.766×10^{-7}	kWh
Foot-pounds/minute (ft-lb/min)	1.286×10^{-3}	Btu/min
	0.01667	ft-lb/s
	3.030×10^{-5}	hp
	3.241×10^{-4}	kg-cal/min
	2.260×10^{-5}	kW
Foot-pounds/second (ft-lb/s)	7.717×10^{-2}	Btu/min
	1.818×10^{-3}	hp
	1.945×10^{-2}	kg-cal/min
	1.356×10^{-3}	kW
Gallons (gal)	3785	cm^3
	0.1337	ft^3
	231	in.^{3}
	3.785×10^{-3}	m^3
	4.95×10^{-3}	yd^3
	3.785	liters
Gallons water (gal H_2O)	8.3453	lb H_2O
Gallons/minute (gal/min)	2.228×10^{-3}	ft^3/h
	0.06308	liters/s
	8.0208	ft^3/h
Gallons H_2O/minute (gal H_2O/min)	6.0086	tons H_2O/day
Grams (g)	2.205×10^{-3}	lb

(continued)

Table 2.3-31. (continued)

Multiply	By	To obtain
Grams/cubic centimeter g/cm^3	62.43	lb/ft^3
	0.03613	lb/$in.^3$
Grams/liter (g/liter)	8.345	lb/1000 gal
	0.062427	lb/ft^3
Horsepower (hp)	42.44	Btu/min
	33,000	ft-lb/min
	550	ft-lb/s
	1.014	hp (metric)
	10.70	kg-cal/min
	0.7457	kW
	745.7	W
Horsepower (boiler)	33.479	Btu/h
	9.803	kW
Horsepower-hours (hph)	2547	Btu
	1.98×10^4	ft-lb
	641.7	kg-cal
	2.737×10^5	kg-m
	0.7457	kWh
Inches (in.)	2.540	cm
Inches of mercury (in. Hg)	0.03342	atm
	1.133	ft H_2O
	0.03453	kg/cm^2
	70.73	lb/ft^2
	0.4912	lb/$in.^2$

(continued)

Table 2.3-31. (continued)

Multiply	By	To obtain
Inches of water	0.002458	atm
	0.07355	in. Hg
	0.002540	kg/cm^2
	5.202	lb/ft^2
	0.03613	$lb/in.^2$
Kilograms (kg)	2.205	lb
	1.102×10^{-3}	tons (short)
Kg/cm^2	0.9678	atm
	32.81	ft H_2O
	28.96	in. Hg
	2048	lb/ft^2
	14.22	$lb/in.^2$
Kilowatts (kW)	56.92	Btu/min
	4.425×10^4	ft-lb/min
	737.6	ft-lb/s
	1.341	hp
	14.34	kg-cal/min
	10^3	W
Kilowatthours (kWh)	3415	Btu
	2.655×10^4	ft-lb
	1.341	hph
	850.5	kg-cal
	3.671×10^5	kg-m
Liters	10^3	cm^3
	0.03531	ft^3

(continued)

Table 2.3-31. (continued)

Multiply	By	To obtain
	61.02	in.^{3}
	10^{-3}	m^3
	1.308×10^{-3}	yd^3
	0.2642	gal
Meters (m)	100	cm
	3.281	ft
	39.37	in.
	10^{-3}	km
	10^3	mm
	1.094	yd
Meters/minute (m/min)	1.667	cm/s
	3.281	ft/min
	0.05468	ft/s
	0.06	km/h
	0.03723	mph
Meters/second (m/s)	196.8	ft/min
	3.281	ft/s
	3.6	km/h
	0.06	km/min
Pounds (lb)	16	oz
	256	drams
	7000	gr
	0.005	tons (short)
	453.5924	g
	1.21528	lb (troy)
	14.5833	oz (troy)

(continued)

Table 2.3-31. (continued)

Multiply	By	To obtain
Pounds of water (lb/H_2O)	0.01602	ft^3
	27.68	m^3
	0.1198	gal
Pounds of water/minute (lb H_2O/min)	2.670×10^{-4}	ft^3/s
Pounds/cubic foot (lb/ft^3)	0.01602	g/m^3
	16.02	kg/m^3
	5.787×10^{-4}	lb/$in.^3$
Pounds/square inch (lb/$in.^2$)	0.06804	atm
	2.307	ft H_2O
	2.036	in. Hg
	0.07031	kg/cm^2
Temp (°C)+273	1	abs. temp (°C)
Temp (°C)+17.78	1.8	temp (°F)
Temp (°F)+460	1	abs. temp (°F)
Temp (°F)-32	5/9	temp (°C)
Tons (long)	1015	kg
	2240	lb
	1.12000	tons (short)

(continued)

Table 2.3-31. (continued)

Multiply	By	To obtain
Tons (metric)	10^3	kg
	2205	lb
Tons (short)	2000	lb
	32000	oz
	907.18486	kg
	2430.56	lb (troy)
	0.39237	tons (long)
	29156.56	oz (troy)
	0.90718	tons (metric)
Tons of water/24 h	83.333	lb of water
	0.16643	gal/min
	1.3349	ft^3/h

REFERENCES

1. 1976 Generation Planbook. Pacemaker Plants/Mansfield. Designing Large Central Stations to Meet Environmental Standards, McGraw-Hill, Inc. pp. 25-34.

2. Laseke, B.A. EPA Utility FGD Survey: December 1977 - January 1978. EPA 600/7-78-051a, March 1978.

3. Durker, K.R. Survey of Pennsylvania Power's Bruce Mansfield Power Generating and Flue Gas Desulfurization System. U.S. Environmental Protection Agency, Research Triangle Park, July 14, 1977.

4. Laseke, B.A. EPA Utility FGD Survey: December 1977 - January 1978. EPA 600/7-78-051a, March 1978.

5. American Air Filter - Better Air is our Business. Cane Run FGD Plant Description. 1976. pp. 1-63.

6. Laseke, B.A. EPA Utility FGD Survey: December 1977 - January 1978. EPA 600/7-78-051a, March 1978.

7. Beard, J.B. Scrubber Experience at the Kentucky Utilities Company Green River Power Station. Environmental Technologist Kentucky Utilities Company, 1976.

8. Laseke, B.A. EPA Utility FGD Survey: December 1977 - January 1978. EPA 600/7-78-051a, March 1978.

9. VanNess, R.P., and J. Jonakin. Paddy's Run No. 6 SO_2 Removal System - a status report. Presented at the 12th annual Purdue University Air Quality Conference, Louisville Gas and Electric Co., Indianapolis, Indiana, November 8, 1973.

10. Laseke, B.A. EPA Utility FGD Survey: December 1977 - Janauary 1978. EPA 600/7-78-051a, March 1978.

CONTENTS

2.4 SLUDGE DISPOSAL

Page

2.4.1 Introduction 2.4-1

2.4.2 Environmental and Land-use Impacts 2.4-1

2.4.3 Disposal Practices 2.4-4

- 2.4.3.1 Ponding 2.4-5
- 2.4.3.2 Landfilling 2.4-6
- 2.4.3.3 Chemical Fixation 2.4-8
- 2.4.3.4 Alternative Disposal Methods 2.4-14

2.4.4 Economics 2.4-16

References 2.4-23

Bibliography 2.4-25

2.4 SLUDGE DISPOSAL

2.4.1 Introduction

Lime FGD systems reduce the quantity of air pollution from coal combustion; however, they also produce a large amount of sludge that can create a solid waste and/or water pollution problem. This section is concerned with the techniques of sludge disposal, the associated environmental impacts in terms of land use and water pollution, and the reported costs of disposal. The major studies on FGD sludge disposal have been reviewed giving particular attention to environmental impacts, disposal practices, and disposal costs.

Analyses show that FGD sludge can contain toxic trace elements; therefore one environmental concern is that sludge leachate is a possible source of groundwater contamination. Another concern stems from the large amounts of sludge generated and the extensive land required for its disposal. This is a serious problem in areas where land is at a premium. Land reclamation is still another related concern.

Several sludge disposal methods are available and currently in use. However, limited knowledge regarding the degree of protection provided versus cost makes selection of the proper technology a difficult task. Absence of direct U.S. Environmental Protection Agency (EPA) regulations adds to selection problems.

The assessment indicates that ponding or landfilling of raw sludge in a disposal site lined with some impermeable material may provide adequate environmental protection against leaching. However, questions regarding life expectancy of lining materials and the effect this type of disposal may have on land reclamation are still unanswered. Chemical fixation of the sludge before disposal appears to be the best technique available, in that it provides permanent protection, reduces disposal volume, and facilitates reclamation.

Alternative sludge disposal methods such as use of the sludge in byproducts show promise, but they have not been sufficiently developed to permit full-scale utilization.

2.4.2 Environmental and Land-use Impacts

Coal-fired electric generating stations commonly dispose of their solid wastes by ponding or landfilling. Pollution of ground or surface waters is a potential hazard, especially when toxic trace elements are present, and coal ash and sludge from FGD systems normally contain varying amounts of trace elements.

The composition of the waste product (sludge) that is discharged from the FGD system is a function of the particular FGD process, ash removal practice, and coal composition. Up to 1.4 million tons/yr of fly ash and sludge can be produced by a 1000-MW plant, which means tremendous quantities of waste material must be disposed of. The total quantity could amount to as much as three times the tonnage of fly ash normally removed from a power station.[1]

It is difficult to predict accurately the amount of sludge that will be produced by an FGD system because numerous variables affect the quantity and quality of scrubber sludge. Major variables include FGD efficiency, the amount of coal fired, impurities in the coal, sulfur and ash content of the coal, the amount of lime used, and particulate removal efficiency.[2]

Disposing of sludge is a difficult task not only because of the massive quantities involved but also because of its generally poor chemical and physical properties. The physical properties of FGD sludge can affect handling and disposal methods and also any possible future land use. Primary sludge constituents that affect the chemical and physical properties are water, fly ash, calcium sulfate, and/or sulfite. Raw sludge drained from an FGD system can contain as much as 85 to 95 percent water; thus, water is the major component in the volume of waste to be disposed of and affects its physical properties. Fly ash is a source of trace elements, and calcium sulfite can create dewatering difficulty and produce undesirable physical characteristics.

Generally, FGD sludge components from lime FGD systems consist of calcium sulfite hemihydrate, calcium sulfate dihydrate, fly ash, and unreacted absorbent. The relative amounts of each depend on many factors, including the kind and amount of fuel burned, the efficiency of sulfur dioxide and particulate removal, the purity of the lime, and the boiler type and operating practices. Sulfate sludges are more easily dewatered than sulfite sludges and thus result in smaller volumes to be handled. Generally, the higher the water content in the sludge, the less desirable are its physical characteristics. Furthermore, sulfate sludges are nonthixotropic, whereas sulfite sludges are thixotropic. Thixotropic materials will reliquify upon agitation, which affects structural properties and subsequent land utilization.[2]

Chemical characteristics of FGD sludge are a function of elements in the coal, the scrubber absorbent, and operating parameters of the system. Toxic trace elements are of great concern in sludge disposal. Most trace elements in FGD sludge originate in the coal and are carried to the sludge by the fly ash and combustion gases. Even if the practice is to remove fly ash prior to scrubbing, some fly ash and trace elements are inevitably carried over to the sludge. The absorbent and the scrubbing water are also minor sources of trace elements.

The major toxic trace elements found in fly ash and FGD sludge are mercury, zinc, arsenic, lead, and selenium. Because FGD sludge contains trace elements, its disposal presents a potential hazard to both ground and surface waters; how much of a hazard depends on the solid characteristics, weather, topography, and proximity of ground and surface waters.

Overflow of sludge disposal ponds and runoff from sludge landfills can pollute nearby surface waters (lakes, streams, rivers), thereby providing pathways through which trace elements and dissolved solids can enter into waters from which drinking water supplies may be withdrawn. Although the effects should be no greater than those due to fly ash disposal alone, a potential for pollution does exist.

Because raw FGD sludge is very permeable, sludge liquid (liquor) or other liquids can pass through, and possibly pollute the groundwater by leaching. The permeability of FGD sludge is a measurement of the rate at which water can pass through the material. Untreated scrubber sludge has a permeability of 10^{-4} to 10^{-5} cm/s, which is approximately the same as fine sand.[2]

Elements can be leached from the sludge solids and carried into the underlying soil as liquids move through the sludge. Leachate composition is a function of the chemical composition of the sludge, the solubility of the elements present, pH, and the age of the disposal site. It is possible for an aquifer beneath a disposal site to become contaminated, and it might be years before such pollution is discovered by a groundwater user. It is therefore important to determine the rate of pollutant migration and the chemical composition of the seepage. The U.S. Army Corps of Engineers and others have been conducting such research for the EPA for several years.[1,3]

The final environmental consideration concerns the impact of FGD sludge disposal on land use. The large quantities and poor physical characteristics of sludge warrant serious consideration of land use and reclamation problems. If the sludge is not treated, it may not remain sufficiently dry to support loads. The result might be a quicksand-like material covering large areas. Over a 20-yr period, a 1000-MW power plant could require 860 to 1100 acres (10 ft deep) to dispose of lime FGD sludge with a 50 percent solids content.[2]

Reclamation of disposal sites depends on the load-bearing capacity of the waste. The thixotropic nature of a sulfite sludge could prevent reclamation and pose a permanent hazard to the public and to wildlife. Sludge that has been sufficiently dewatered and is nonthixotropic could be reclaimed and revegetated to produce an area adequate for recreation or building.[2]

Weathering also has a detrimental effect on the physical properties of sludge. The EPA has conducted research in this area as well.[4] Sludge disposal areas are also possible sources of fugitive dust. This problem is confined to specific areas, however, and can be alleviated through proper site management.[5]

2.4.3 Disposal Practices

Lime FGD systems produce large amounts of sludge. Undesirable physical and chemical properties, the presence of trace elements that may be toxic, and the volume of the sludge have created environmental concerns related to disposal. These concerns include not only extensive land use, but also prevention or limitation of the release of pollutants to surface or groundwaters.

Although FGD sludge could be used to produce gypsum for use in wallboard or portland cement, most utility power plants will dispose of the sludge. Sludge utilization is not economically attractive at the present time.[6]

Coal-fired power plants in the United States have been disposing of coal ash by ponding or landfilling for many years and have extended these conventional ash disposal practices to the disposal of FGD sludge. However, several utilities chemically treat or fix the wastes before disposal. Fixation improves the structural properties of the waste and tends to decrease leaching. It is possible that the EPA will eventually require sludge fixation before landfilling or other methods of disposal.

Groundwater pollution due to leachate migration or runoff, the physical strength of the sludge, and land use are the major environmental problems associated with sludge disposal. At present, no Federal criteria specifically apply to FGD sludge disposal, but the Resource Conservation and Recovery Act of 1976, which was signed into law in October 1976, requires that the EPA establish regulations or guidelines for disposal of wastes from air pollution control systems such as FGD.[7] Guidelines for FGD sludge and coal ash disposal have been prepared and are under reivew. The EPA has been directing efforts since mid-1975 toward preparation of technically supportable documents that can be used to set FGD waste disposal guidelines.[8]

The EPA has indicated that disposal of raw sludge is unacceptable.[2] In September 1975, the EPA declared "permanent land disposal of raw (unfixated) sludge to be environmentally unsound because it indefinitely degrades large quantities of land." Eventually, however, disposal of raw FGD sludge may be allowed if means of containing it are proved to be environmentally acceptable. A recent study for the EPA has stated that chemical fixation or seepage elimination through the use of impermeable liners are both possible methods by which FGD wastewaters can meet current criteria for groundwater or drinking water quality.[5]

Approximately 10 state regulatory agencies have considered FGD sludge disposal. They have allowed ponding of untreated sludges, landfilling of fixed sludges, and discharge of excess water.[2]

It appears that ponding with a liner or in an impermeable basin will probably be satisfactory as long as land reclamation is neither a legal requirement nor a plant necessity. If sound structural properties are required, chemical fixation of the sludge, possibly in conjunction with an impermeable basin, would provide sufficient strength and minimize leaching to groundwater.[5]

Ponding and landfilling are the major disposal options, but ocean dumping and mine disposal are possible alternatives. The latter two have been actively investigated by the EPA. Mine disposal also has a potential side benefit of preventing mine subsidence. The following subsections describe current FGD sludge disposal alternatives.

2.4.3.1 Ponding--

Common practice among utilities is to pond FGD sludge. This is the easiest and sometimes the cheapest means of sludge disposal. Sludge is disposed of by ponding at almost all of the facilities that have operating lime FGD systems. Table 2.4-1 lists these facilities. At some installations, ponding is used to store the sludge temporarily or to dewater it before final disposal.

Table 2.4-1. LIME FGD SYSTEMS THAT DISPOSE OF SLUDGE BY PONDING[2]

Utility	Plant
Arizona Public Service	Four Corners 1, 2, and 3
Kansas City Power and Light	Hawthorn Nos. 3 and 4
Kentucky Utilities	Green River Nos. 1 and 2
Louisville Gas and Electric	Cane Run No. 4

Typically, sludge is pumped or trucked to a pond where it settles to 35 to 45 percent solids.[9] Supernatant (sludge liquor) can be recycled to the scrubbing system. The use of ponds for sludge disposal requires the availability of sufficient land near the power plant.

The techniques of pond construction and operation are well established. Wet disposal virtually precludes the fugitive-dust problems that sometimes occur in dry disposal operations. Holding volume can be increased by building up the sides of the disposal pond. At the end of its useful life, the disposal site can be left undisturbed for a hydraulic head to form over the matrix.

Although ponding appears to eliminate the complications of other disposal techniques, it has disadvantages. Compared with other methods, ponding requires a larger volume to hold the sludge; this volume may or may not be available. Also, because the sludge may remain fluid, concerns may arise about the eventual abandonment of the site and the possible removal of large areas of land from any future use.

Ponding techniques were developed with little or no concern for their environmental effects. Groundwater contamination and overflow into surface waters are now important considerations. Possible pollutants from ponding of sludge include soluble toxic species, quantities of species not considered toxic, and excessive suspended and dissolved solids. The chemical oxygen demand of sulfite sludge is also a potential problem.

The water above and in the sludge provides a force for percolation and the contamination of any existing underground aquifer. Pond liners can be used to form a barrier between the sludge and the aquifers. Both clay and synthetic materials have been used as liners. Potential problems include the unknowns, such as what effect the sludge has on a liner and what the actual life expectancy of a liner is. In view of these uncertainties, a system designed to monitor the effectiveness of the liner should be incorporated into the disposal site.[1]

2.4.3.2 Landfilling--

When limited land availability and/or economic considerations make ponding unfeasible for FGD sludge disposal, landfilling of dried sludge may prove practicable. Like ponding, landfilling has historically been used by utilities for disposal of coal ash. The major difference between the landfilling of ash and sludge landfilling is that the ash is often collected dry, whereas sludge must be processed into a dry state suitable for landfilling.

One operating lime FGD system, at the Paddy's Run No. 6 unit of Louisville Gas and Electric, disposes of slurry by landfilling. This method offers several advantages. For example, dry disposal by landfilling largely precludes reclamation problems associated with ponding. It also eliminates the need for dams or dikes, which may be required for disposal by ponding. This method of disposal is also more efficient in terms of total land requirements because much of the water has been removed. Rainfall onto a dry disposal area can be treated as runoff, whereas with ponding, it creates the possibility of runoff and adds to the supernatant. Leaching is believed to be less of a problem with landfills because the amount of water in and above the sludge has been reduced. The primary disadvantages of dry sludge disposal by landfilling are the handling and processing steps added to the disposal system in order to convert the sludge into a dry form.

The simplest method of reducing the water content of FGD sludge is to add dry solids such as fly ash, if available. To produce a drier product, it is usually necessary to apply further treatment. Popular methods include interim ponding, clarification, centrifugation, and vacuum filtration. Interim ponds or clarifiers are often primary dewatering devices. An interim pond provides temporary storage as well as clarification and sludge settling. Clarifiers achieve the same result. These methods are not adequate to produce a sludge dry enough for landfilling, except at several western facilities, where an arid climate, low-sulfur fuels, and other factors make interim ponding alone a feasible disposal technique. Vacuum filtration or centrifugation can be applied in conjunction with these primary dewatering techniques to achieve a higher sludge solids content. Centrifuges produce concentrated sludge and good clarification. They have achieved up to 75 percent solids content in TVA tests, but their primary drawback is high power consumption. Vacuum filtration is used for further dewatering at Paddy's Run No. 6.[2] This method has achieved solids contents of 55 to 70 percent.[6] Dewatering of the sludge to a minimum of at least 50 percent is necessary to ensure handling capabilities.

Landfilled dried sludge is believed to pose less of an environmental hazard than ponded raw sludge. Dried sludge, however, has the potential of rewatering when exposed to rainfall; so the possibility of groundwater and surface water pollution, although reduced, is not eliminated. When water from rainfall or subsurface flow contacts the sludge, it can create leachate problems if allowed to percolate through the sludge. Additionally, if the runoff from such a landfill is permitted to seep through nearby land, leachate can pollute nearby streams or the groundwater surface through leaching.[5]

Properly designed and managed landfills can minimize pollution potential. Drains upstream of the landfill can prevent subsurface flow into a landfill, and a landfill liner, such as that discussed for ponding, can trap leachates at the bottom.

Covering the landfilled material can greatly reduce the quantity of leachate while affording protection against the possibility of rewatering and preventing surface leaching. Landfilling dried sludge appears to be more environmentally acceptable than ponding in that it reduces the volume of material to be disposed of and does not necessarily preclude future productive use of the site.

2.4.3.3 Chemical Fixation--

Sludge fixation, although not a disposal technique in itself, is a means of physically and chemically stabilizing FGD sludge to reduce its pollution potential and make its disposal more environmentally acceptable. A nontoxic, nonleachable, load-supportive material is the desired end-product. Table 2.4-2 lists the installations that fixate FGD sludge. Fixation has been described as an encapsulation process because chemical and physical changes that provide a barrier against pollutant migration are effected in the sludge.[3]

Table 2.4-2. LIME FGD SYSTEMS THAT FIXATE SLUDGE

Utility	Plant	Process
Columbus and Southern Ohio Electric	Conesville 5	IUCS
Duquesne Light	Elrama	IUCS
	Phillips	IUCS
Pennsylvania Power	Bruce Mansfield 1 and 2	Dravo

Only Dravo Corporation and IU Conversion Systems, Inc., offer sludge fixation processes that are considered well enough developed and tested to be commercially viable. In general, these fixation processes reduce the solubility of major chemical species by a factor of two or four, reduce the permeability by at least an order of magnitude, and improve the structural properties of the sludge. The environmental effects of disposal of fixated sludge can be less than those from other available sludge disposal methods, but the additional cost of chemical fixation must be weighed against the benefits.

Unless proper procedures are followed in disposal of fixated sludge, the potential for chemical pollution still exists. For example, if rainwater is allowed to percolate through the sludge, unbound chemical species can be leached out.[5] Tests have also indicated that fixation does not appear to improve leachate quality with respect to trace metals. In fact, some of the trace elements in the leachate may even be due to the fixation chemicals.[5] Even though fixation does not appear to reduce leachate concentrations of trace elements, it can reduce the concentration of major chemical species by 25 to 50 percent, reduce the permeability of the material, and allow more efficient (volume) disposal.[5]

Dravo system--The Dravo Corporation process is being used in connection with a full-scale FGD system at the Bruce Mansfield Power Station of Pennsylvania Power Co. in Shippingport, Pennsylvania. Experience was also gained on the Dravo sludge treatment system during a 2-yr demonstration program at the Phillips Generating Station of Duquesne Light in South Height, Pennsylvania.

Dravo has been involved with FGD systems since the early 1970's. Its research led to the development of sludge fixation processes that are based on an additive called Calcilox^{R} (also developed by Dravo). Calcilox is a hardening agent derived from blast furnace slag. When added to FGD sludge, it effects changes in the sludge that result in an end product that alleviates some of the concerns associated with the disposal of raw, untreated scrubber sludge. The product is more physically stable, stronger, and less permeable than untreated wastes.

Three different disposal variations of the sludge fixation process are available from Dravo, each involving the addition of Calcilox. The full impoundment method is used at the Bruce Mansfield Station. Scrubber sludge, Calcilox, and hydrated lime are mixed, and the slurry is piped to a final disposal pond, where the mixture cures or stabilizes. Excess water or supernatant is pumped back to the scrubbing system to be recycled. The correct amount of Calcilox addition is determined through testing, so that the sludge will possess an unconfined compressive strength of 4.5 tons/ft^2 after 30 days. The curing time is not particularly important in the full impoundment method. At Mansfield, the slurry will cure beneath the supernatant to form a stabilized mass. The site can eventually be used for light industrial development or for recreational purposes.[10]

If dry handling methods are preferred, Dravo offers two such methods--interim ponding and mechanical dewatering. Interim ponding was demonstrated at the Phillips Power Station of Duquesne Light Company. With the method, a mixture of sludge and Calcilox is pumped to small curing ponds. After it has cured, the sludge is excavated and moved to a landfill.

When dry fly ash is available (i.e., collected before the scrubbing system) the sludge can be dewatered by mechanical means, then mixed with Calcilox and fly ash. The resultant mixture can be sent directly to a landfill. After a curing period of 5 to 6 days, the fixated sludge would be spread on the landfill. This is Dravo's mechanical dewatering process, and it has not yet been used at any full-scale installation.

The water content of FGD sludge is slightly reduced by stabilization with Calcilox and depends on both the original water content of the sludge and the amount of Calcilox added. The solids content of the sludge increases only slightly when interim ponding or full impoundment is used because little dewatering is involved. Thus, the required disposal volume is approximately unchanged with Calcilox stabilization.[2]

Sludge fixated with Calcilox will not reslurry unless it is subjected to severe remolding. Even if it does reslurry, the sludge will harden again if left undisturbed. There appears to be no tendency to reslurry after the slurry has been cured for about 90 days.[2] Sludge disposal areas can support loads; thus they can utlimately be used for development. If the full impoundment method is used, the final site can be used, possibly as a landfill, depending on drainage provisions.[2]

Treatment of sludge with Calcilox improves the environmental acceptability of its disposal. Leachate quantity is reduced, and tests indicate that permeability is reduced by at least a factor of 10. Permeability coefficients normally range from 10^{-4} to 10^{-5} cm/s for raw sludges and 10^{-5} to 10^{-6} cm/s for Calcilox-treated sludge, and values as low as 10^{-8} cm/s have been attained.[10] Dravo has proposed using sludge treated with extra Calcilox (to ensure the lowest possible permeability) as a liner for the disposal area.

The full impoundment method requires a larger volume for disposal than simple dry landfilling. Dikes and/or dams may be necessary to contain the sludge during the settling and curing processes. Other disadvantages of this method include an inability to monitor the quality of the sludge as it cures and an increased amount of leachate during pond operation (because of the pool of supernatant above the curing sludge).

An advantage of the Dravo full impoundment system, in addition to reduced leachate and lower permeability, is that it does not require dry fly ash, which is necessary for most dry disposal systems. Also, the disposal area can be reclaimed for building development or used as a lake. It is not known, however, what effect fixated sludge would have on the water quality of a recreational lake reclaimed from a disposal site.

Compared with the ponding of raw FGD sludge, Dravo's interim ponding system allows for somewhat more efficient land use. Based on density, however, the volume of the disposal area is still one and a half times that necessary for dry landfilling of untreated sludge.[2] This method also has the potential advantage of not requiring dry fly ash. Final disposal is dry; thus, dams or dikes are unnecessary. This reduces costs and eliminates a potential problem area. Environmental and land reclamation advantages discussed for the full impoundment method apply to the interim ponding technique as well.[2]

The processes of curing, excavation, and final disposal occur in sequence and somewhat complicate disposal by adding handling steps. This system uses a series of steps, and problems in any one of these steps can disrupt operation of the system.

In summary, Dravo offers either wet or dry disposal systems. No dry fly ash is required, and tests show the processes are applicable to sludge with various sulfite and sulfate contents. Dravo has not indicated any uses of the sludge fixated with Calcilox other than for landfilling or as a liner.[7]

Further investigation appears to be appropriate regarding changes in properties (if any) of Calcilox-fixated sludge over a period of years. Furthermore, because the only facility that produces Calcilox is in Pennsylvania, application of the process might be geographically, and therefore economically, limited.

IU Conversion Systems--IU Conversion Systems, Inc. (IUCS) is another vendor with full-scale commercial experience in the stabilization of FGD sludge. The company markets a physicochemical fixation system called Poz-O-Tec^{R}, which it claims produces a sludge that is ecologically acceptable. This system has been proven through full-scale operation.[10]

The technology developed by IUCS over the past 25 years utilizes pozzolanic (cementitious) reaction principles. The Poz-O-Tec process, which was developed about 8 years ago, provides a method of including FGD sludge in a chemically stabilized matrix. The sludge is trapped and encapsulated within a matrix, which is hard and relatively impermeable.[11] The treatment system involves sludge dewatering and the addition of lime, dry fly ash, and additives.

IUCS systems have been used or demonstrated at various locations across the country. The largest system is at the Conesville Station of Columbus and Southern Ohio Electric Company. It uses the Poz-O-Tec process on sludge from two units generating a total of 800 MW.

An IUCS interim processing plant has been operating at the Elrama Station of Duquesne Light Company since November 1976. This system treats wastes from an FGD system that now treats 200 of the total 500 MW. A full-scale facility under construction will be capable of treating all the wastes generated when the FGD system is completed. An IUCS system has been constructed at Duquesne's Phillips Station. These two systems handle approximately 700,000 and 450,000 tons/yr, respectively.[2]

IUCS gained experience by operating a pilot plant at the Mohave Station of Southern California Edison Company. In this demonstration project, Poz-O-Tec was used as landfill, as a base course for parking lots and roads, as an aggregate for concrete, and finally, as a land base upon which a condominium was constructed.

G.W. Carson and Co., the predecessor to IUCS, also demonstrated the process and possible uses for the fixed wastes. Poz-O-Tec was used to prepare a base course of a parking area and as a pond liner for fly ash disposal ponds at two generating stations.[10]

Sludge disposal using the IUCS process involves three steps: dewatering, mixing, and placement or disposal of the fixated sludge. Drum vacuum filters are generally used to dewater the sludge. If necessary, they may be preceded by thickeners. Centrifuging is an alternative method of dewatering. After the moisture content has been reduced, the sludge is thoroughly mixed with dry fly ash, lime, and an additive. The end product can be hauled by truck, rail, barge, or conveyor belt to a disposal site or to wherever it will be used.[10]

The chemical reactions involved in the Poz-O-Tec process are similar to those occurring in portland cement, but they proceed at a slower rate. Sludge particles and fly ash are bound together in a rigid, physically stable matrix that will not reliquify.

Physical characteristics of Poz-O-Tec-treated sludge vary, depending on the raw scrubber sludge and the degree of treatment. The consistency of the end product can be made to resemble dirt, sand, or solid rock. The IUCS process increases the density of the sludge, resulting in a smaller volume to be disposed of. Compared with that produced by the combined ponding of raw scrubber sludge and fly ash, the disposal volume can be halved by the Poz-O-Tec process. Compared with the separate disposal of ponded raw sludge and landfilled fly ash, the volume savings is approximately 15 percent.[2]

Strength and compressibility are also improved by the Poz-O-Tec process. The fixated sludge is very incompressible, and landfilled material will support normal foundation loads. The material gains strength with curing and shows no tendency to reslurry upon reworking or exposure to water. The properties have been compared with that of a "low-strength concrete-like material." The chemical bonding of the sludge particles improves stability and preserves the desirable physical properties.[2]

Stabilizing FGD sludge with the IUCS process decreases land requirements and improves reclamation potential. The use of this stabilization process also decreases the quantity of leachate and improves the quality because the chemical bonding creates less soluble species. To date, trace element leaching data have been inconclusive because of low concentrations and variable results. Further testing is being carried out by the U.S. Army Corps of Engineers at its Waterways Experiment Station.[2,12]

Permeability is another important factor in determining environmental acceptability. Tests on Poz-O-Tec material have shown values of 10^{-6} to 10^{-7} cm/s with curing. Thus, the IUCS process reduces permeabilities of scrubber sludge to levels of 100 to 1000 times lower than those of raw sludges. The physical encapsulation process that occurs in the IUCS process limits water contact. Improved leachate and low permeability reduce the mass of leached material per unit of time from 200 to 2000 times less than that in unstabilized scrubber sludge.[2]

Sludge fixated by the IUCS process can be landfilled or disposed of in a quarry, mine, or ravine. Sludge produced at the Columbus and Southern Ohio Electric Company's Conesville Station is being disposed of on flatlands. Over the normal life expectancy of the plant, a 100-ft hill, which will eventually be reclaimed by placement of topsoil and revegetation, will be created.[10]

If the fixated sludge is to be used as a byproduct rather than simply disposed of, IUCS modifies the process with more additives to further increase the physical stability of the material. Pond liners and road bases for public highways and parking lots have been constructed with Poz-O-Tec. Other by-product possibilities have included use as a synthetic aggregate for concrete blocks and as a subbase for a warehouse.[2]

Although the IUCS process can be used to stabilize sludge from any calcium-based (lime, limestone, dual alkali) FGD system, applicability depends on the availability of dry fly ash. A minimum of 10 percent fly ash is required for the process. Although it has not been demonstrated, IUCS claims the Poz-O-Tec process can be applied at plants where fly ash is collected wet. According to IUCS, substitutes for fly ash can also be used, and they are currently conducting research to determine possible substitutes. The IUCS system could be applied to almost all of the existing or planned utility FGD systems because most are calcium-based and have available fly ash.

Scrubber sludge fixation by the Poz-O-Tec process offers several advantages when compared with other disposal techniques. Dams or dikes, which may be needed for ponding of raw or treated sludge, are unnecessary. Because it is a dry disposal technique, more efficient land use (disposal volume) is realized. Furthermore, the environmental impact is decreased because a separate disposal site is no longer needed for fly ash.

Sludge treated by the Poz-O-Tec system exhibits greater strength and density and possesses lower permeabilities (by several orders of magnitude) than raw FGD sludge. This low permeability can eliminate the need for liners because the material can be equal to or even less permeable than standard requirements for landfill liners. Reduced leachate potential and the good physical properties of this material simplify eventual reclamation of the disposal site. Successful demonstrations of byproduct utilization also increase the attractiveness of the Poz-O-Tec process.

2.4.3.4 Alternative Disposal Methods--

Ponding and landfilling are the established sludge disposal methods. They will probably continue to be the primary sludge disposal techniques even though other techniques have been used and continue to be investigated. Alternative methods such as mine filling and ocean disposal appear to offer benefits, but could adversely affect the environment. Current EPA programs for investigating alternative disposal methods are designed to provide answers to the major questions.

Mine disposal--Coal mine disposal of FGD waste has long interested engineers because of existing railroad links between coal mines and power plants and because of the need for material to fill the empty areas left by mining. Only recently, however, have studies been undertaken concerning the technical, environmental, and economic factors connected with mine disposal. An initial review suggests that two types of mines are best suited for FGD waste disposal: active, surface-area coal mines located between the Rocky Mountains and Appalachia and active, room-and-pillar, underground coal mines of the East, including Appalachia. Unit 2 of the Milton R. Young Station of Minnkota Power Cooperative in North Dakota is currently depositing flue-gas cleaning wastes in a surface lignite mine; and utilities in Ohio and Minnesota have considered mine disposal projects, but have not adopted them.[13]

Mine disposal of FGD wastes could increase the total dissolved solids in waters recharged by leachate from the disposal site. When part of the overburden is to be placed in the mined-out strip before the deposit of FGD wastes, the wastes might remain above the groundwater table, with the result that there would be less likelihood of pollution from the leachate.[13]

Ocean disposal--Arthur D. Little is currently studying ocean disposal of FGD waste for the EPA. Lack of land for sludge disposal sites is one reason why many power plants in the Northeast cannot fire coal. The same installations, however, often have access to the ocean; and if ocean disposal were proven environmentally acceptable, they might convert from burning oil to firing coal. Still, until better data about the technical, environmental, and economic aspects of ocean dumping are available, disposal of sulfite-rich FGD wastes on the Continental Shelf or in the deep ocean appears unadvisable.[13]

Various environmental problems could result from ocean disposal of FGD wastes. Fine-grained, untreated FGD wastes could "pave" over the coarse-grained sand particles that cover the ocean floor and are most conducive to marine life on the Continental Shelf. In addition, the settling and resuspension of wastes could expose various marine organisms to harmful concentrations of suspended sediments. The effects of sulfite toxicity, oxidation, and dissolution on the marine environmental could also prove detrimental. Finally, both treated and untreated wastes may have trace-element concentrations that exceed acceptable levels for marine life.[13]

Sludge utilization--Utilization of FGD sludge appears to hold limited promise. Although various applications and byproducts are known to be technically feasible, few, if any, can be economically justified in the United States at present. As a result, disposal will be practiced by an overwhelming majority of utilities with FGD scrubber sludge.

Primary examples of FGD sludge utilization were discussed earlier in connection with the IUCS Poz-o-Tec process. Sludge treated by this process has been used as a base for highways, parking lots, a warehouse, and also a pond liner. Unfortunately, the overall demand for sludge for these uses is not expected to exceed that which could be supplied. Nevertheless, diversion of some of the waste into useful end products could lengthen the useful life of a disposal site.[2]

Other uses of scrubber sludge are in the production of construction materials and in agricultural and chemical recovery. One of the principal byproducts of lime and limestone FGD systems can be calcium sulfate (gypsum). In Japan, gypsum from FGD systems is used extensively in the production of wallboard and portland cement. This type of process has been demonstrated in the United States, but its widespread use is doubtful because this country has large, natural sources of dry gypsum, whereas Japan has little or none.[9]

Other construction materials that can be derived from FGD sludge include brick, aerated and poured concrete, and mineral wool. The technology for producing these products was developed at the Coal Research Bureau at West Virginia University. These sludge-derived products have shown properties comparable to their natural counterparts.[9]

Agricultural applications of scrubber sludge are also being investigated. These include soil amendment and fertilization. The Coal Research Bureau has shown that the calcium in sludge can be beneficial to plant growth and that sludge could possibly be used to adjust pH of the soil. The TVA is conducting research for the EPA on the production of fertilizer from lime/limestone scrubbing wastes. Thus far, only two commercial applications of FGD sludge for agricultural purposes are known.[2] This usage of sludge is expected to be limited and will depend largely on local conditions.

A final consideration is the utilization of FGD sludge for chemical recovery. An EPA program now underway is investigating the conversion of scrubber sludge to hydrogen sulfide (from which elemental sulfur can be derived) and calcium carbonate (limestone). Several different processes and methods have been suggested, but none has been used on a full-scale basis. Most would result in elemental sulfur or some sulfur compound, and extensive sludge processing would be required for any chemical recovery. Element sulfur, however, is abundant and relatively inexpensive, so there is little economic incentive to develop a recovery plant.[2]

Sludge utilization has been proven to be technically feasible. Limited markets may be found, but the prospects for widespread use of large amounts of sludge appear dim. Lack of economic competitiveness is the primary constraint. As a result, most FGD sludge will probably be disposed of by ponding or landfilling.

2.4.4 Economics

Table 2.4-3 lists the flue-gas cleaning and sludge-disposal practices of all utility scrubbers that were operating in November 1977 and using throwaway processes. Although the information is now somewhat outdated (e.g., the Will County 1 Station of Commonwealth Edison and the St. Clair 6 Station of Detroit Edison are no longer operational), it still gives a fair indication of how utilities deal with FGD sludge. Ponding remains the most common form of disposal.[2]

The costs of disposal can vary greatly. They depend on the quantity and quality of the sludge, the nature and location of the disposal site, and associated design, material, labor, and delivery considerations. These factors may differ widely from site to site.

An EPA-sponsored symposium on flue gas desulfurization, held November 8 though 11, 1977, provided some useful information on sludge disposal costs. Two presentations of particular value on sludge disposal techniques used by utilities and their costs are discussed in the following paragraphs.

Boston and Martin gave a presentation regarding the operation of the Conesville Generating Station of Columbus and Southern Ohio Electric.[14] This generating station uses the IUCS sludge disposal technology. Unit 5, a 400-MW boiler, fires coal with a sulfur content of 4.5 percent. Unit 6, which began operation in June 1978, is similar to Unit 5. The lime-based

Table 2.4-3. FLUE-GAS-CLEANING AND SLUDGE-DISPOSAL PRACTICES FOR UTILITY SCRUBBERS USING THROWAWAY PROCESSES AND OPERATIONAL ON NOVEMBER 1, 1977[2]

Utility	Station name and unit number	MW equiv. oil scrubber(s)	Fly ash removal	SO_2 removal	Reagent	Oxidation	Thickener	Vacuum filter	Centrifuge	Settling pond[a]	Blend with fly ash	Blend with fly ash and lime	Commercial fixation		Ultimate disposal	
													IUCS	DRAVO	Pond	Landfill
Arizona Public Service	Cholla 1	115	Mechanical, R-C flooded disc	R-C packed tower, unpacked tower	Limestone										●	
Arizona Public Service	Four Corners 1, 2, 3	575	Chemico venturi	b	Alkaline ash, lime		●								●	
Columbus & Southern Ohio Electric	Conesville 5, 6	806	ESP	UOP-TCA	Lime[c]		●						●			●
Commonwealth Edison[d]	Will County 1	140	ESP, B&W venturi	B&W 2-stage perforated plate	Limestone		●			●		●				●
Detroit Edison[d]	St. Clair 6	163[c]	Mechanical, ESP, Lurgi Venturi, and Peabody spray tower	b	Limestone										●	
Duquesne Light	Elrama	500	Mechanical, ESP	Chemico venturi	Lime		●						●			●
Duquesne Light	Phillips	400	Mechanical, ESP	Chemico venturi	Lime		●						●			●
Indianapolis Power & Light	Petersburg 3	515	ESP	UOP-TCA	Limestone								●			●
Kansas City Power & Light	Hawthorn 3, 4	180	C-E marble bed	b	Lime		●								●	
Kansas City Power & Light	La Cygne 1	840	B&W venturi	B&W 2-stage countercurrent tray	Limestone										●	

(continued)

Table 2.4-3. (continued)

Utility	Station name and unit number	MW equiv. oil scrubber(s)	Fly ash removal	SO_2 removal	Reagent	Oxidation	Thickener	Vacuum filter	Centrifuge	Settling pond[a]	Blend with fly ash	Blend with fly ash and lime	Commercial fixation		Ultimate disposal	
													IUCS	DRAVO	Pond	Landfill
Kansas Power & Light	Lawrence 4, 5	525	C-E rod venturi	C-E spray tower	Limestone		●							●		
Kentucky Utilities	Green River 1, 2	64	Mechanical, AAF venturi	AAF mobile bed	Lime									●		
Louisville Gas & Electric	Cane Run 4	190	ESP	AAF mobile bed	Carbide sludge		●							●		
Louisville Gas & Electric	Paddy's Run 6	65	ESP	C-E marble bed	Carbide sludge		●	●			●				●	
Minnesota Power & Light	Aurora 1, 2	116	Elbair spray impingement	b	Alkaline ash									●		
Minnesota Power & Light	Clay Boswell 3	350	Elbair spray impingement	b	Alkaline ash		●							●		
Minnkota Power Cooperative	Milton R. Young 2	450	ESP	ADL/CEA spray tower	Alkaline ash and lime		●	●							●	
Montana Dakota Utilities	Lewis and Clark	50	Mechanical	R-C flooded disc	Limestone										●	
Montana Power	Colstrip 1, 2	716	CEA venturi	CEA countercurrent spray, KOCH tray	Alkaline ash, lime					●					●	
Northern States Power	Sherburne 1, 2	1500	C-E rod venturi	C-E single-stage marble bed	Alkaline ash, lime	●	●								●	
Pacific Power & Light	Dave Johnston 4	330	Chemico venturi	b	Alkaline ash, lime					●						●

(continued)

Table 2.4-3. (continued)

Utility	Station name and unit number	MW equiv. oil scrubber(s)	Fly ash removal	SO_2 removal	Reagent	Oxidation	Thickener	Vacuum filter	Centrifuge	Settling pond[a]	Blend with fly ash	Blend with fly ash and lime	Commercial fixation		Ultimate disposal	
													IUCS	DRAVO	Pond	Landfill
Pennsylvania Power	Bruce Mansfield 1, 2	1650	Chemico venturi	Chemico venturi	Lime		●							●	●	
Public Service of Colorado	Arapahoe 4	100	Mechanical, ESP, and UOP-TCA	b	Alkaline ash					●						●
Public Service of Colorado	Cherokee 1, 3, 4	600	Mechanical, ESP, and UOP-TCA	b	Alkaline ash		●			●						●
Public Service of Colorado	Valmont 5	80	Mechanical, ESP, and UOP-TCA	b	Alkaline ash					●						●
South Carolina Public Service Authority	Winyah 2	140	ESP	B&W venturi	Limestone		●								●	
Southwest Public Services	Harrington 1	350	ESP	C-E marble bed	Waste $CaCO_2$ slurry		●								●	
Springfield City Utilities	Southwest 1	200	ESP	UOP-TCA	Limestone		●	●			●					●
Texas Utilities	Martin Lake 1	750	ESP	R-C spray tower	Limestone		●		●		●					●
Texas Utilities	Monticello 3	750	ESP	Chemico spray tower	Limestone										●	
TVA	Widows Creek 8	550	ESP	TVA venturi, grid tower absorber	Limestone										●	

[a] Settling pond, a pond not used for final disposal.

[b] Where there is no SO_2 removal device indicated there is some incidental SO_2 removal that results in SO_3/SO_4 sludge from the scrubbing process.

[c] Lime contains 4 to 6% MgO.

[d] These units are no longer operating as SO_2 removal systems.

[e] One half of rated capacity is being scrubbed.

FGD system that cleans the flue gases produces a sludge that is 30 percent solids. This sludge slurry is sent to a primary thickener, a secondary thickener (if needed), then pumped to the vacuum filters. After the sludge is filtered, it is thoroughly mixed with lime and fly ash in a pug mill to achieve fixation. The mixture is then conveyed to the disposal area, which is part of the existing ash pond.

The sludge fixation process equipment is owned by IUCS and leased to Columbus and Southern Ohio Electric Company (C&SOE), whose personnel operate and maintain the system. This arrangement resulted in minimal capital costs, but annual operating costs are relatively high. Preparation of the disposal site and work connected with the ash system have accounted for the only capital costs incurred by C&SOE to date. This has amounted to $1,639,000 for both units. Annual operating costs for Unit 5, including the IUCS fee, are $2,928,000 or 1.63 mills/kWh. The annual cost for both units is expected to be $3,271,000 or 0.91 mills/kWh.[14]

The waste disposal system at the Bruce Mansfield Power Plant was the topic of another presentation at the FGD Symposium that the EPA sponsored in November 1977.[15] Dravo Corporation designed and constructed the waste disposal system for both units at this power plant. The full impoundment method using Calcilox additive was decided upon, with 100 percent redundancy specified for the sludge treatment and transport systems.

After being thickened to 25 to 35 percent solids, the sludge is pumped to a mixing tank for the addition of Calcilox. From the mixing tank the mixture must be pumped approximately 7 miles to the disposal site, a 1400-acre valley that has been made into a reservoir by construction of a 400-ft impoundment dam. The system has been designed as a closed-loop operation, and runoff and supernatant can be returned to the FGD system. Monitoring wells surrounding the disposal site are used to check groundwater quality.

The capital cost of the Dravo disposal system for both units is reported to be $90,000,000 or $54.5/kW. This value is in reasonable agreement with the $50.70/kW reported to FPC. The operating cost is reported to be $3.81 per ton of slurry solids, which is equivalent to approximately 0.55 mills/kWh, a value considerably larger than the 0.04 mills/kWh reported to FPC. As at Conesville, the annual operating costs should decrease with the addition of the second unit.[15]

Although FGD sludge is being fixated at both the Bruce Mansfield and Conesville plants, costs differ significantly. This is partially due to site conditions and the difference in disposal techniques, but the primary reason involves the leasing (Conesville) versus ownership (Bruce Mansfield) arrangement. Actual costs over a projected 30-yr life span would probably be comparable.

A recent EPA report offers some broad generalizations about the costs of disposing of FGD waste.[16] This report calculated the lifetime revenue requirements for new 200-, 500-, and 1500-MW power plants using various disposal methods. These calculations are presented in Table 2.4-4. It should be stressed that the estimates assume a limestone, rather than lime, scrubbing process and do not include the cost of the process. Only the costs of the disposal alternatives are estimated.

Table 2.4-4. SUMMARY OF THE REVENUE REQUIREMENTS DURING THE 30-YEAR LIFE OF A NEW POWER PLANT[a] FOR VARIOUS FGD-WASTE-DISPOSAL METHODS[16]

Case[b]	Total actual lifetime revenue requirement, $	Lifetime average unit revenue requirements, mills/kWh	Total present-worth lifetime revenue requirement, $[c]	Levelized unit revenue requirements,[d] mills/kWh
Untreated				
200 MW	58,750,000	2.30	20,204,800	2.03
500 MW	97,757,800	1.53	33,612,100	1.35
1500 MW	203,309,200	1.06	69,819,400	0.94
Dravo				
200 MW	94,392,200	3.70	33,368,200	3.36
500 MW	175,764,900	2.76	62,052,600	2.50
1500 MW	375,002,700	1.96	133,456,200	1.79
IUCS				
200 MW	89,013,000	3.49	30,584,100	3.08
500 MW	131,224,200	2.06	45,381,700	1.83
1500 MW	254,498,000	1.33	88,798,600	1.19
Chemfix				
200 MW	111,241,300	3.36	38,655,100	3.38
500 MW	167,942,300	2.63	59,099,300	2.38
1500 MW	333,190,900	1.74	119,154,500	1.60

[a] Basis

Over previously defined power plant operating profile. 30-yr life: 7000 h for first 10 yr; 5000 h for next 5 yr; 3500 h for next 5 yr; 1500 h for next 10 yr.

Midwest plant location, 1980 operating costs.

Constant labor cost assumed over life of project.

[b] New plants, coal analysis (wt.%): 3.5% S (dry), 16% ash, fly ash removed with SO_2 to meet New Source Performance Standards.

[c] Discounted at 10% to initial year.

[d] Equivalent to discounted process cost over life of power plant.

REFERENCES

1. Rossoff, J., and R.C. Rossi. Mid-Term Report Study of Disposal of Byproducts from Nonregenerable Flue Gas Desulfurization Systems, Volume II: Technical Discussion. U.S. Environmental Protection Agency, Washington, D.C., December 1, 1973.

2. Michael Baker, Jr., Inc. State-of-the-Art of FGD Sludge Fixation. Research Project 786-1, Task 3 (Draft). Electric Power Research Institute, Palo Alto, California, August 1977.

3. Mahloch, J.L., D.E. Averett, and J.J. Bartos, Jr. Pollutant Potential of Raw and Chemically Fixed Hazardous Industrial Wastes and Flue Gas Desulfurization Sludges Interim Report. EPA-600/2-76-182.

4. Radian Corporation and Southern California Edison Company. The Environmental Effects of Trace Elements in the Pond Disposal of Ash and Flue Gas Desulfurization Sludge. Electric Power Research Institute, Palo Alto, California, September 1975.

5. Rosoff, J., R.E. Rossi, et al. Disposal of Byproducts from Nonregenerable Flue Gas Desulfurization Systems: Second Progress Report. EPA-600/ 7-77-052, May 1977.

6. Radian Corporation. Evaluation of Lime/Limestone Sludge Disposal Options. EPA-450/3-74-016, November 1973.

7. Smith, C.L. Sludge Disposal by Stabilization - Why? In: Proceedings of the Second Pacific Chemical Engineering Congress, Inter-American Confederation of Chemical Engineering, Asian Pacific Confederation of Chemical Engineering, Denver, August 28-31, 1977.

8. Jones, J.W., and T.G. Brna. Environmental Management of Effluents and Solids Wastes from Steam Electric Generating Plants. In: National Conference on the Interagency Energy/Environment Research and Development Program, Washington, D.C., June 6-7, 1977.

9. Radian Corporation. Disposal of Lime/Limestone Sludges. EPA-68-02-0046, September 10, 1973.

10. Radian Corporation (Draft). Byproduct/Waste Disposal for Flue Gas Cleaning Processes. EPRI RP 786-2, Electric Power Research Institute, Palo Alto, California, March 29, 1977.

11. Taub, S.I. Treatment of Concentrated Waste Water to Produce Landfill Material. In: International Pollution Engineering Exposition and Congress, Anaheim, California, November 10, 1976.

12. FGD Quarterly Report, Vol. 1, No. 2. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, August 1977.

13. Jones, J.W. Disposal of Flue-gas-cleaning Wastes. Chemical Engineering, 84 (4):79-85, February 14, 1977.

14. Boston, D.L., and J.E. Martin. Full-scale FGD Waste Disposal at the Columbus and Southern Ohio Electric's Conesville Station. In: Symposium on Flue Gas Desulfurization, Hollywood, Florida, November 8-11, 1977.

15. Lobdell, L.W., E.H. Rothfuss, Jr., and K.H. Workman. Eighteen Months of Operation Waste Disposal System, Bruce Mansfield Power Plant, Pennsylvania Power Company. In: Symposium on Flue Gas Desulfurization, Hollywood, Florida, November 8-11, 1977.

16. Barrier, J.W., H.L. Faucett, and L.J. Henson. Economics of Disposal of Lime/Limestone Scrubbing Wastes: Untreated and Chemically Treated Wastes. EPA-600/7-78-023a, February 1978.

BIBLIOGRAPHY

Jones, J.W. Research and Development for Control of Waste and Water Pollution from Flue Gas Cleaning Systems. In: EPA Symposium on Flue Gas Desulfurization, New Orleans, March 8-11, 1976.

Leo, P.P., and J. Rossoff. Control of Waste and Water Pollution from Power Plant Flue Gas Cleaning Systems: First Annual R and D Report. EPA-600/7-76-018, Washington, D.C., October 1976.

Energy Resources Company, Inc. Utility Analysis of Coal Transportation Availability, Task 2: Transportation and Disposal of Coal Ash and FGD Sludge for the New England ESECA Candidates, Contract No. CO-05-60573, Federal Energy Administration, Washington, D.C., February 1977.

PEDCo Environmental, Inc. Summary of the State-of-the-Art of Flue Gas Desulfurization Sludge Disposal. Federal Energy Administration, Washington, December 1977.

Jones, J.W. Chemical Engineering, February 14, 1977, pp. 79-85.

FGD Sludge Disposal Process Cost Assessment. Federal Energy Administration, Washington, D.C., February 1978.

SECTION 3

PROCESS CONTROL

3.1 INTRODUCTION

This section of the Data Book deals with the basic science of process control and its application to the design and operation of a lime scrubbing FGD system. When used in this section, the word "control" refers to process control and not to instrumentation hardware, which is discussed in Section 4.13. Process control is not chemical control, which concerns the conditions that cause scale formation or that affect SO_2 removal. Chemical control is discussed as part of the process chemistry in Section 2.

In a continuous operation, such as a lime scrubber, process control is required for safe and stable operation. The primary goal of the control system in a lime scrubbing system is to ensure that sulfur dioxide emissions from the scrubber meet the emission limits. This section of the Data Book will discuss techniques of controlling the following variables to meet the emission limits:

- Lime feed
- Solids
- Flue gas fluctuations

In addition to emission control, pH and lime feed control must be designed to reduce excess chemical use. Solids and pH control are used to prevent scaling and plugging. The quantity of reheat is controlled to reduce energy consumption while yielding adequate emission dispersal. Liquid levels are controlled to prevent tanks and vessels from overflowing. Flocculants, which are fed to thickeners to improve clarification, must also be controlled.

Process control has evolved into a distinct engineering area, with a conceptual approach and a language that differs from that of other engineering disciplines. Section 3.2 of this Data Book illustrates, primarily through example, this approach and some of its specialized terms.

Section 3.3 examines several of the major subsystems of a lime scrubber control system to illustrate the practical application of the approach to the control problems of a scrubber.

The section describes control techniques being used, or that have been proposed, to solve such problems as control of reheat and lime feed rate.

The controller and the control valve, which are common to every control system, are discussed in Section 3.4. The action of a proportional, integral, and derivative (PID) controller is described, followed by a discussion of the linearity of the control element (usually a control valve), which is a frequent cause of poor control system performance.

CONTENTS

3.2 PRACTICAL APPLICATION OF PROCESS CONTROL

Page

3.2.1 Basic Control 3.2-1

3.2.2 Control Improvements 3.2-4

  3.2.2.1 Avoidance of Component Errors 3.2-4
  3.2.2.2 Elimination of DIsturbances, Cascade Control 3.2-6
  3.2.2.3 Elimination of Disturbances, Feed Forward 3.2-6

3.2.3 Control Systems 3.2-9

Bibliography 3.2-12

3.2 PRACTICAL APPLICATION OF PROCESS CONTROL

3.2.1 Basic Control

A study of process control is not concerned with the physical hardware of a plant, but with plant variables, which are measurable properties of an operating process. A tank of water, for example, has properties that include temperature, liquid level, and total weight, any of which can be used as a control variable. A flowing stream of slurry has the properties of density, pressure, solids content, and flow rate; and any or all of these could be a variable for use in process control.

The objective in the control of a continuous process is to maintain variables at the desired values; the basic building block to accomplish this is the control loop. There are two types of loop: a feed-forward loop and a feedback loop. The term "control loop" implies a circle, and a loop consists of six components interconnected to form a continuous path. A simple feedback control loop is shown in Figure 3.2-1. The six components of the loop are:

1. A sensor, which is a device that measures the value of a controlled variable. In Figure 3.2-1, the controlled variable is the temperature of the stack gas; the sensor is a thermocouple. The sensor in any control loop is connected, either mechanically or with a pneumatic or electronic signal, to:

2. A comparator. This is a mechanical or electrical mechanism that compares the value of the controlled variable with a set point. The set point is a mechanical connection or a signal that defines the desired value of the controlled variable. The difference between the actual and the desired value, which may be either positive or negative, is the error that exists at any instant in time. The comparator is always connected to, and is physically located, in the same housing as,

3. A controller. A process controller is a computing device that performs a mathematical manipulation based on the value of the error. As a result of the mathematical manipulation, a controller generates a signal, known as the controller output. The output signal is connected to:

4. A control element. This is usually a control valve that moves mechanically in response to the output signal from the controller. In the example of stack gas reheat, the control valve opens or closes slightly as the output signal increases or decreases. The control element must modify:

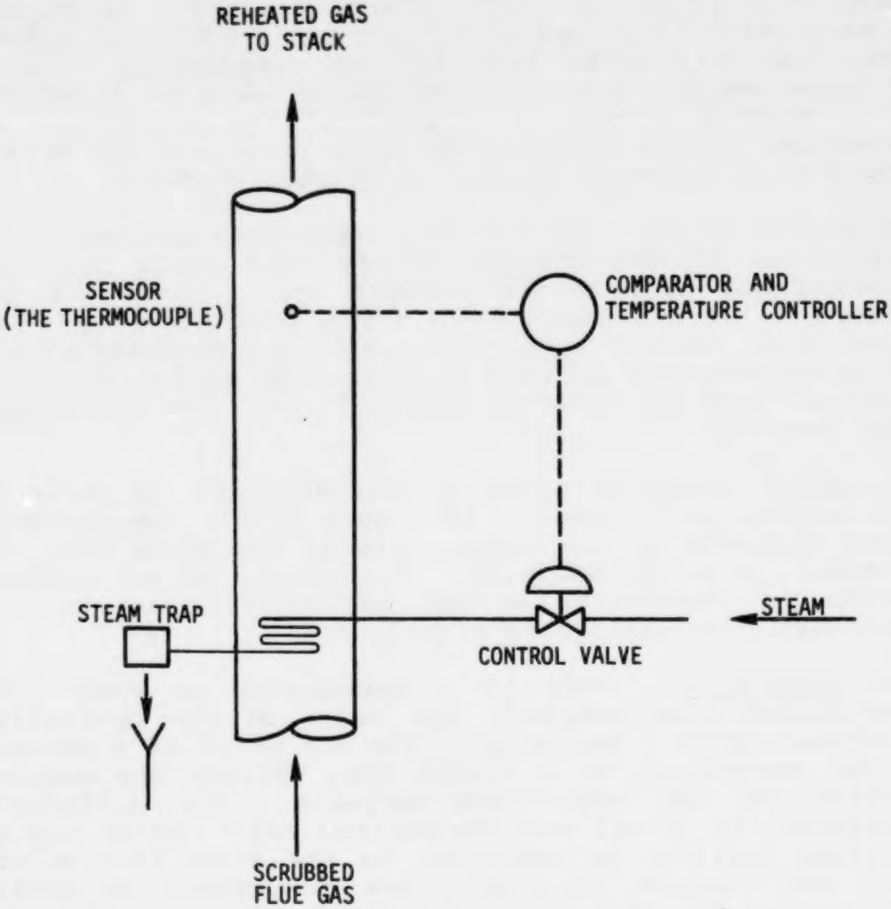

REHEATED GAS TO STACK
SENSOR (THE THERMOCOUPLE)
COMPARATOR AND TEMPERATURE CONTROLLER
STEAM TRAP
STEAM
CONTROL VALVE
SCRUBBED FLUE GAS

Figure 3.2-1. Feedback control loop in a stack gas reheat control system.

5. The manipulated variable. In this example, the flow rate of steam changes as the control valve opens or closes. In some manner, the manipulated variable must affect the controlled variable. The connecting link between the two is:

6. The process. A portion of the plant hardware and a flowing stream of fluid are integral components of every control loop. In this example, a change in steam flow rate changes steam coil pressure and, consequently, steam condensing temperature. This in turn changes the flow rate of heat through the walls of the steam coil, thereby changing stack gas temperature, which is the measured variable. The circular path is completed.

A feedback control loop is therefore a complex interaction of mechanical and mathematical components. If the loop is to operate properly, each component must be compatible with the others, and each must be properly designed to accomplish its intended function. Even if the loop is mechanically correct, however, it may or may not be adequate to handle a specific control problem. Two concepts provide a route to evaluate the probable performance of a control loop and to indicate whether or not control improvements are indicated.

The first is the concept of disturbance. Any condition of operation either within or external to the control loop that will cause an unintentional change to the controlled variable is said to be a disturbance to that loop. In the example of stack gas reheat, at least two conditions could cause substantial changes to reheat temperature. An increase in stack gas flow rate will cause a drop in temperature, as will a drop in steam pressure. Either of these conditions would constitute a disturbance to the control loop.

The second concept is that of time lag, which is usually negligible in the control of electric power variables, but is a major problem in chemical process control. In the example of stack gas reheat, a time lag is created by the heat-sink effect of the condensate and metal in the steam coil. The more massive the coil, the longer the time lag will be. In pH control, as much as 15 min can elapse following an increase in lime slurry feed rate before a change is noted in the reading of the pH sensing instrument in the recycle tank. On the other hand, some loops have a short time lag; flow rate of a liquid changes almost immediately whenever the control valve position is changed. Most loops have time lags between these extremes, and these can be estimated. Time lag in a loop is estimated in many instances by the volume of process fluid that is affected by the manipulated variable. To change the pH of a large volume, such as the body of liquid in a scrubber, requires more time than to change the pH in a flowing stream in a pipeline. Time lag can also be related to volume or mass of the manipulated stream.

If a feedback control loop has a short time lag (fractions of a second to seconds), it can usually provide adequate control even if disturbances are large (a liquid flow control loop operates well even with large changes in upstream pressure). Conversely, if disturbances are slight, feedback control usually operates fairly well even though the time lag is long (a few seconds or longer). (Feedback control of scrubber pH is adequate if nothing disturbs the system.) Given large or frequent disturbances and a long time lag, feedback control cannot maintain good control, and control improvements are usually necessary.

3.2.2 Control Improvements

3.2.2.1 Avoidance of Component Errors--

The feedback loop must be properly designed. The first step should be an examination of each of the loop components to ensure that each is compatible with the others and able to accomplish its intended function. Problems of compatability include not only the more obvious mechanical, electric, and range-selection matches, but also the problem of nonlinearity, which is emphasized throughout this section of the Data Book.

The greatest problem of hardware inadequacy will be found in the loop sensor. In most instances, these inadequacies are due to the inability of the sensor to measure the controlled variable often because of poor installation or low-cost equipment. In some instances, however, the design is inadequate to measure accurately the actual value of the controlled variable. For instance, in the example of stack gas reheat control, Figure 3.2-2 shows a basic revision that has been made to the sensor to measure the controlled variable more accurately. Temperature can vary significantly from point to point across a large duct. A single thermocouple will probably not measure the true temperature. The average reading of four thermocouples, each in a different part of the duct, is probably more representative of actual temperature.

3.2.2.2 Elimination of Disturbances, Cascade Control--

In Figure 3.2-3, the output of the temperature controller does not directly manipulate the steam control valve, but it is used instead to adjust the set point of a second controller. In a separate control loop, the second controller adjusts the control valve to maintain the flow rate of steam. In this manner, a control loop is separated into two parts, and the technique is known as a cascade. Although there are other reasons for using cascade control, the purpose in this example is to eliminate disturbances that would otherwise be created by

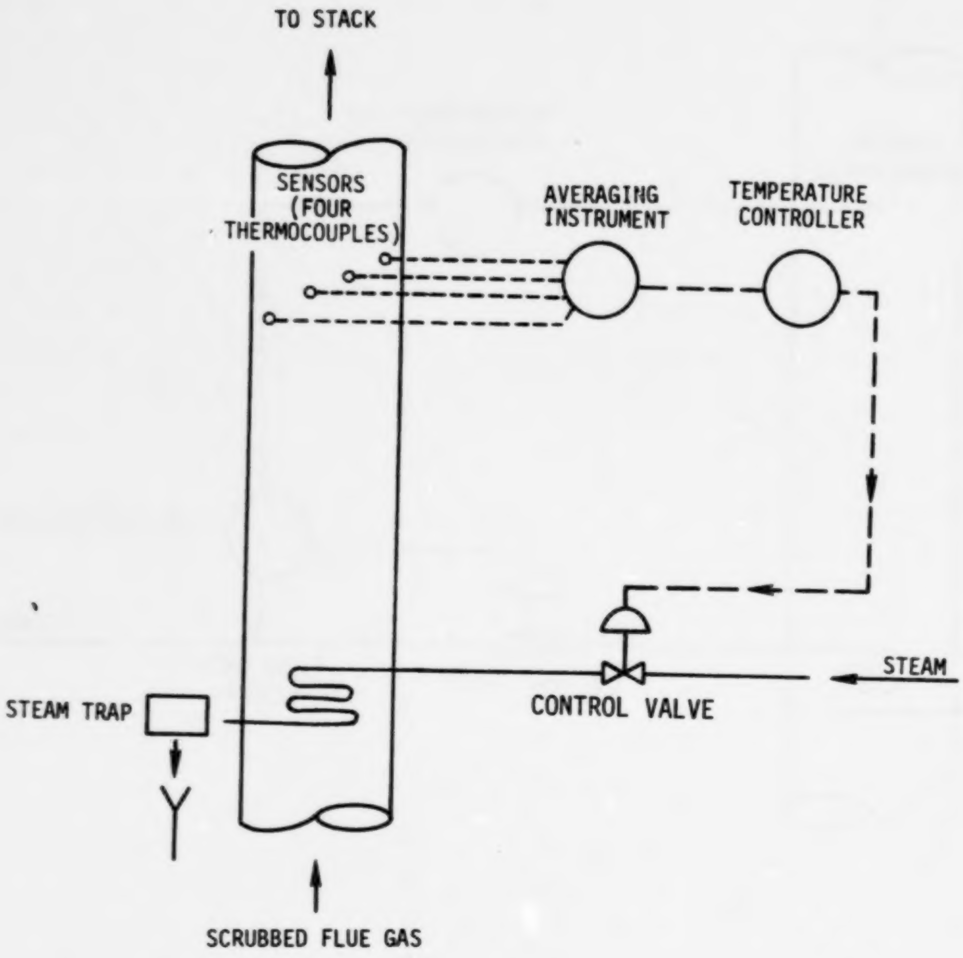

TO STACK
SENSORS (FOUR THERMOCOUPLES)
AVERAGING INSTRUMENT
TEMPERATURE CONTROLLER
STEAM
CONTROL VALVE
STEAM TRAP
SCRUBBED FLUE GAS

Figure 3.2-2. Improved feedback control in stack gas reheat control system.

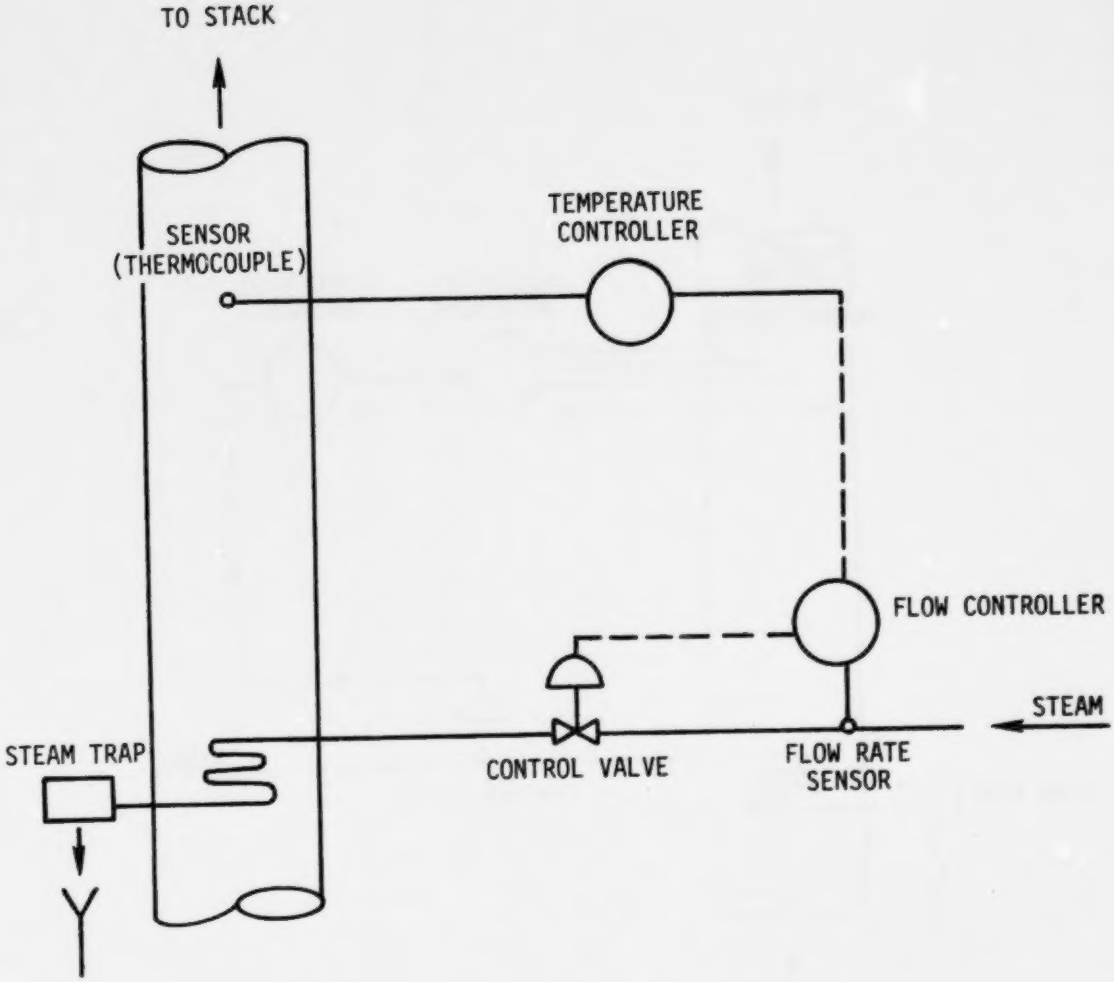

TO STACK
TEMPERATURE CONTROLLER
SENSOR (THERMOCOUPLE)
FLOW CONTROLLER
STEAM
STEAM TRAP
CONTROL VALVE
FLOW RATE SENSOR

Figure 3.2-3. Cascade control.

changes in the manipulated variable. If the temperature controller had been directly connected to manipulate the control valve, any drop in steam flow rate would drop the steam coil pressure, causing the stack gas temperature to drop. The temperature controller, responding to this change, would open the control valve. Eventually the deviation from the set point would be reduced to zero, but a long period would be required in a loop with a fairly large time lag. When cascade control is used, a drop in steam flow rate is measured in the flow control loop, which rapidly opens the control valve. The flow control loop prevents large variations in the steam coil pressure and thereby in the temperature of the flue gas.

Cascade control usually completely prevents disturbances that would otherwise be caused by variations within the manipulated stream. In the example given, if pressure varies, causing steam flow variations, cascade control is a valuable addition to the control loop.

3.2.2.3 Elimination of Disturbances, Feed Forward--

In Figure 3.2-4, the output of the temperature controller passes to the cascade secondary controller through an instrument known as the "feed forward." The principle of feed-forward control differs from that of feedback in a very important respect. In feedback, a disturbance is permitted to cause an error, which is then corrected. Feed forward changes the manipulated variable before the error has occurred by responding to an external condition that, if not compensated for, would become a disturbance to the control loop. Feed forward is connected into the control loop as an equal partner with the feedback controller, and the manipulated variable can be increased or decreased by either one. In Figure 3.2-4, a change in stack gas flow rate would disturb the temperature control loop. If the flow rate of stack gas were measured, steam flow rate could be adjusted in direct proportion to gas rate. If the ratio calculation were conducted accurately, no error would result in the controlled variable of the feedback loop. If the feed-forward ratio adjustment is not entirely accurate, the temperature controller is still in the loop to accomplish final correction and to handle other disturbances.

Major changes in operating conditions can be successfully neutralized with feed-forward control. Feed forward also has the advantage of not requiring absolute accuracy in the instrumentation and can often be implemented with less expensive devices. Even if the signal were slightly inaccurate, the resulting system disturbance would be smaller than with no feed forward at all.

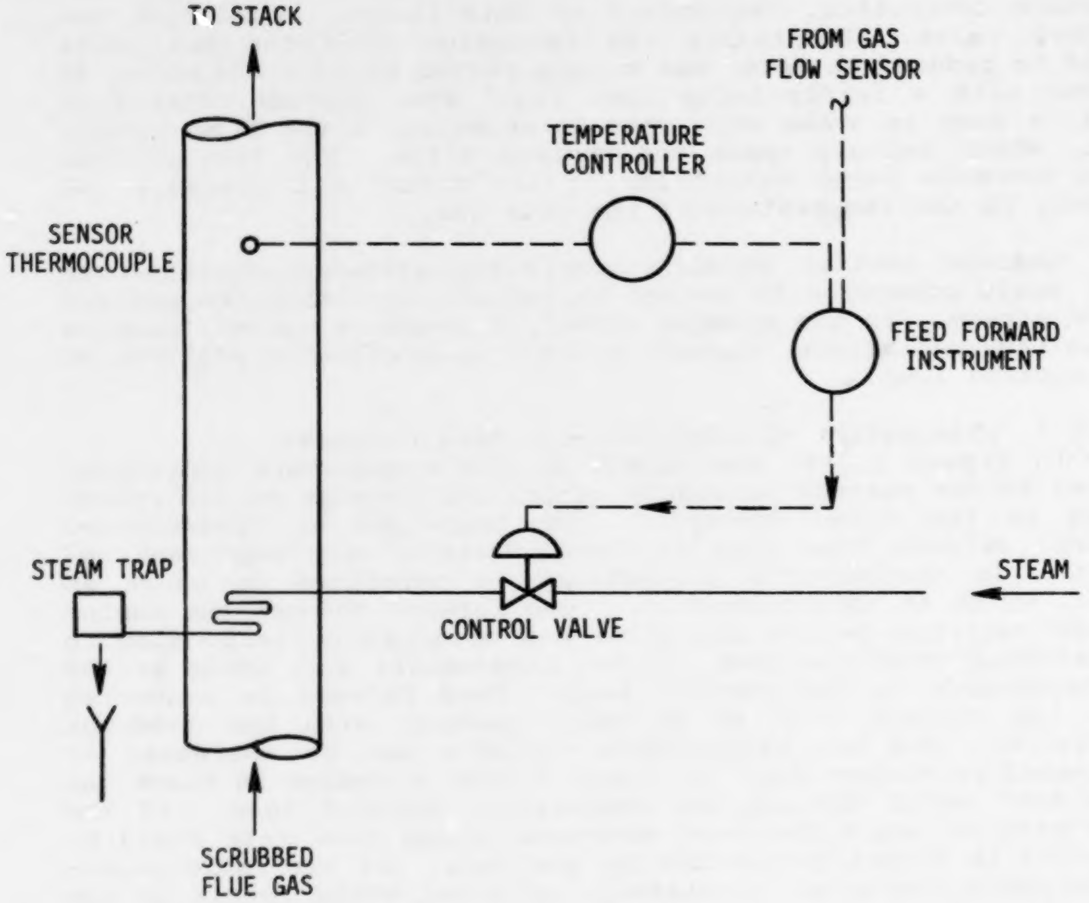

TO STACK
FROM GAS
FLOW SENSOR
TEMPERATURE
CONTROLLER
SENSOR
THERMOCOUPLE
FEED FORWARD
INSTRUMENT
STEAM TRAP
STEAM
CONTROL VALVE
SCRUBBED
FLUE GAS

Figure 3.2-4. Feed-forward control.

3.2.3 Control Systems

In contrast to a control loop, where the objective is to maintain one variable at a fixed value, an integrated control system has the objective of maintaining the overall output from the plant within limits. In a scrubber, the "output" is flue gas discharged to the stack, and an integrated control system includes all adjustments to all variables that influence the quality of this discharge.

A control system therefore consists of many loops, containing every adjustment needed to accomplish the plant objective. Routine manual adjustments by the plant operator are an integral part of the control system. If he changes a valve or a controller set point to maintain a variable at a desired value, he is functioning as a controller in a control loop. System design includes the definition and instrumentation of these manual, or "open," loops in addition to the "closed" loops implemented with automatic instrumentation.

Variables that must be controlled to form a complete control system can be divided into five classifications:

1. Major process variables. In most scrubbers, only two variables define flue gas emissions--stack gas SO_2 content and, possibly, temperature. To date, SO_2 content has been controlled, if at all, only with an open loop. Reheat temperature, if used, is generally a closed loop.

2. Intermediate process variables. The principal intermediate variable (a variable which has an impact on the flue gas characteristics) is scrubber pH, which is usually instrumented.

3. Auxiliary variables. Operations outside the main process stream require coordination with the process. Examples are solids content of thickened sludge and concentration of lime slurry. These can be controlled with both closed and open loops.

4. Inventory variables. Liquid level in process vessels is an inventory variable that is generally fully instrumented. This applies to the scrubber and absorber reaction vessels, slaked lime tank(s), and any other in-process vessels. Instrumentation here can reduce level variations caused by process changes or upsets.

5. Limiting variables. For plant and process safety, certain variables must not exceed given limits. Most plants will contain loops to override other loops,

thereby protecting the plant during abnormal operating conditions. Scrubber vessels have water deluge systems to prevent scrubber lining failures during recirculation pump failures.

Except for limiting variables, which usually develop as details of subsystems, the basic loops of all classifications can be shown on such a diagram as Figure 3.2-5. Without defining details or specifying whether control is to be an open or closed loop, this figure can show the essential requirements for effective control of the scrubber. An important characteristic of a control system is that every flowing stream of material that enters or leaves the scrubber will be a part of at least one control loop; some variable of each stream will be either manipulated or controlled. A thorough control system design will be based on a drawing of this sort that will in turn define the instrumentation needed to execute each loop.

In the following section, some of the subsystems shown on Figure 3.2-5 will be individually examined; however, although they may be studied separately, in no instance does any subsystem stand alone. Every control loop is either disturbed by the action of others or creates a disturbance in others. The approach of control system design is to use these interrelationships as a guide to the complexity required in the instrumentation of each subsystem.

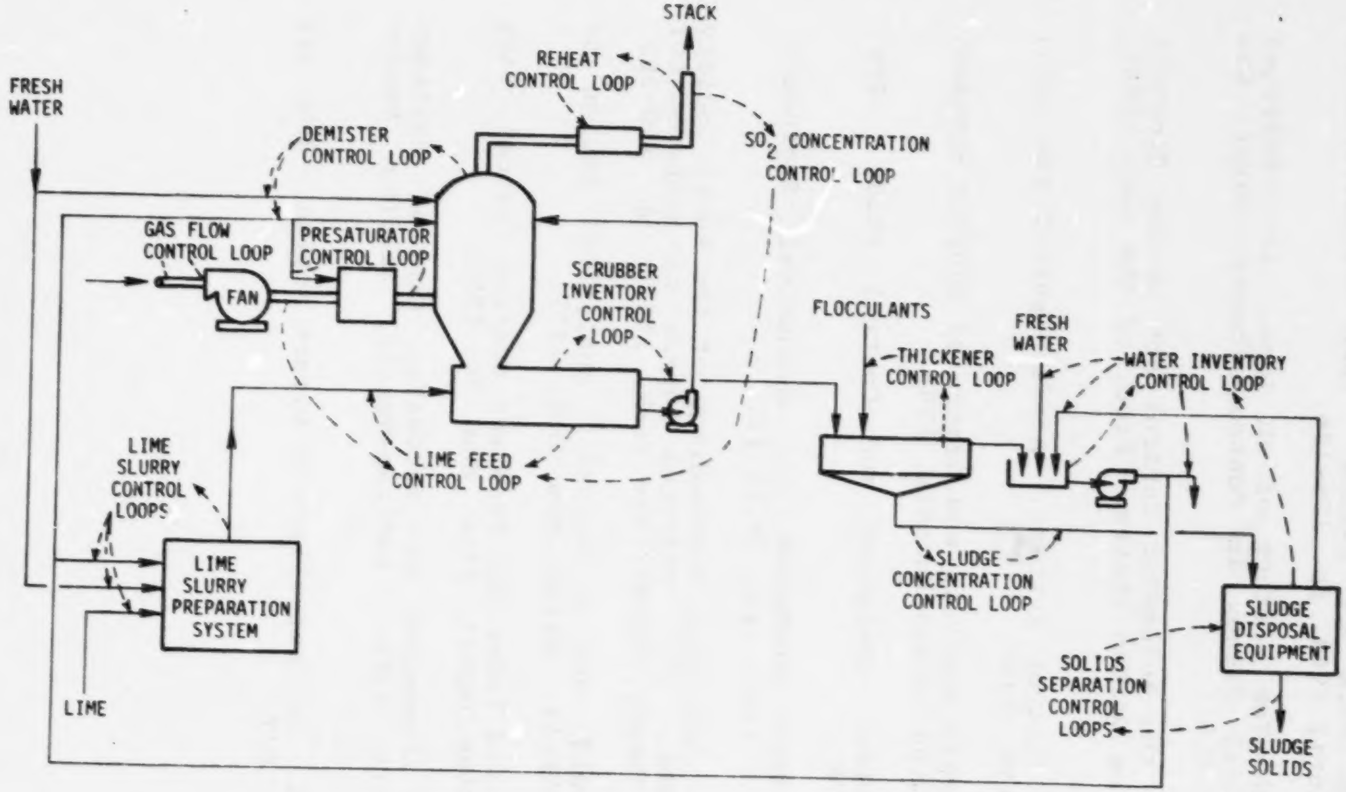

STACK
REHEAT CONTROL LOOP
FRESH WATER
DEMISTER CONTROL LOOP
SO_2 CONCENTRATION CONTROL LOOP
GAS FLOW CONTROL LOOP
PRESATURATOR CONTROL LOOP
FAN
SCRUBBER INVENTORY CONTROL LOOP
FLOCCULANTS
FRESH WATER
THICKENER CONTROL LOOP
WATER INVENTORY CONTROL LOOP
LIME SLURRY CONTROL LOOPS
LIME FEED CONTROL LOOP
LIME SLURRY PREPARATION SYSTEM
SLUDGE CONCENTRATION CONTROL LOOP
SLUDGE DISPOSAL EQUIPMENT
SOLIDS SEPARATION CONTROL LOOPS
LIME
SLUDGE SOLIDS

Figure 3.2-5. Lime scrubber control system.

BIBLIOGRAPHY

Axelby, G. The Gap--Form and Future. IEEE Transactions on Automatic Control, April 1964, pp. 125-126.

Bode, H.W. Feedback--The History of an Idea. In: Selected Papers on Mathematical Trends in Control Theory, Dover, New York, 1964. pp. 106-123.

Cohn, N. State of the Automatic Control Art in the Electric Power Industry of the United States. Proc. of the JACC, 1965. pp. 110-123.

Dorf, R.C. Modern Control Systems. Addison-Wesley Pub. Co., Reading, Massachusetts, 1966.

Dorf, R.C. Time-Domain Analysis and Design of Control Systems. Addison-Wesley, Reading, Massachusetts, 1965.

Lime/Limestone Scrubber Operation and Control Study. EPRI (RP630-2), April 1978.

Marks, L.S. Standard Handbooks for Mechanical Engineers. McGraw-Hill, 7th ed., 1967. pp. 16.33 ff.

Maxwell, J.C. In: Governors Proceedings of the Royal Society of London, 16, 1868. In: Selected Papers on Mathematical Trends in Control Theory, Dover, New York, 1964. pp. 270-283.

Newton, G., L. Gould, and J. Daiser. Analytical Design of Linear Feedback Controls. Wiley, New York, 1957.

Proposed Standards and Terms for Feedback Control Systems, Part 2. A.I.E.E. Committee Report, Elec. Eng. 70, 1951.

Popov, P.E. The Dynamics of Automatic Control Systems. Gostekhizdat, Moscow, 1956. Addison-Wesley, Reading, Massachusetts, 1962.

Vyshnegradskii, I.A. On Controllers of Direct Action. Izv, SPB Technology, Inst., 1877.

CONTENTS

3.3 LIME SCRUBBER CONTROL SUBSYSTEMS

Page

3.3.1 Introduction 3.3-1

3.3.2 Reheat Control 3.3-1

- 3.3.2.1 Fuel-fired Reheat 3.3-1
- 3.3.2.2 Hot Water Reheat 3.3-1
- 3.3.2.3 Steam Reheat 3.3-3

3.3.3 Lime Feed Control 3.3-6

- 3.3.3.1 Nonlinearity 3.3-7
- 3.3.3.2 Time Lag 3.3-7
- 3.3.3.3 Simple pH Control 3.3-9
- 3.3.3.4 Cascade pH Control 3.3-9
- 3.3.3.5 Outlet SO_2 Feedback Control 3.3-9
- 3.3.3.6 Inlet SO_2 Feed-forward Control 3.3-12
- 3.3.3.7 Summary of Lime Feed Rate Control 3.3-14

3.3.4 Slurry Solids Control 3.3-14

- 3.3.4.1 Lime Slurry Feed Control 3.3-16
- 3.3.4.2 Absorber/Scrubber Solids Control 3.3-16
- 3.3.4.3 Thickener Solids Control 3.3-21
- 3.3.4.4 Flocculant Control 3.3-21
- 3.3.4.5 Solids Control Summary 3.3-24

3.3.5 Gas Flow Control 3.3-24

- 3.3.5.1 Pressure Control 3.3-26
- 3.3.5.2 Flow Control 3.3-26
- 3.3.5.3 Boiler Safety 3.3-30
- 3.3.5.4 Fan Control 3.3-30

Bibliography 3.3-33

3.3 LIME SCRUBBER CONTROL SYSTEM

3.3.1 Introduction

In this section, four of the principal control subsystems of a typical scrubber unit are examined. The subsystems control reheat, lime feed rate, slurry solids (including waste disposal), and gas flow.

3.3.2 Reheat Control

Several types of reheat systems are being used in lime scrubbers. Fuel-fired reheat, either direct or indirect; steam reheat, direct or indirect; and hot water reheat must be controlled differently. This section will discuss some of the control techniques for each technique.

In addition, temperature sensing is also important irrespective of the type of reheat used. In Figure 3.2-1, a single sensor is used to measure the temperature of the reheated flue gas. This type of measurement is adequate if the measuring location is isokinetic and system accuracy and reliability are not important. To improve gas temperature measurement and to ensure the continuous monitoring if a single thermocouple fails, however, the multiple sensor shown in Figure 3.2-2 should be used.

3.3.2.1 Fuel-fired Reheat--

Gas- or oil-fired, direct or indirect, the control systems are similar for fuel-fired reheaters, and they are the simplest of all reheat controls. As shown in Figure 3.3-1, changes in stack gas temperature vary the fuel supply to the burner. Although it will not be discussed in detail here, the burner system requires several control loops. As the fuel supply changes, the amount of air must be varied to maintain proper combustion. In addition, several limiting loops are required to stop the fuel flow in case of flameout or combustion blower failure. Multiple burners may be required in flue gas systems to obtain adequate turndown. A single burner normally has a turndown capacity of 3:1.

3.3.2.2 Hot Water Reheat--

Two control posibilities are available to control hot water reheat systems. The temperature of the water can be changed or the heat transfer coefficient and log mean temperature difference can be changed in the heat exchanger by changing the flow rate. In either control loop, the quantity of energy in the hot water supply system must be capable of reheating the gas to the maximum desired temperature at full gas flow.

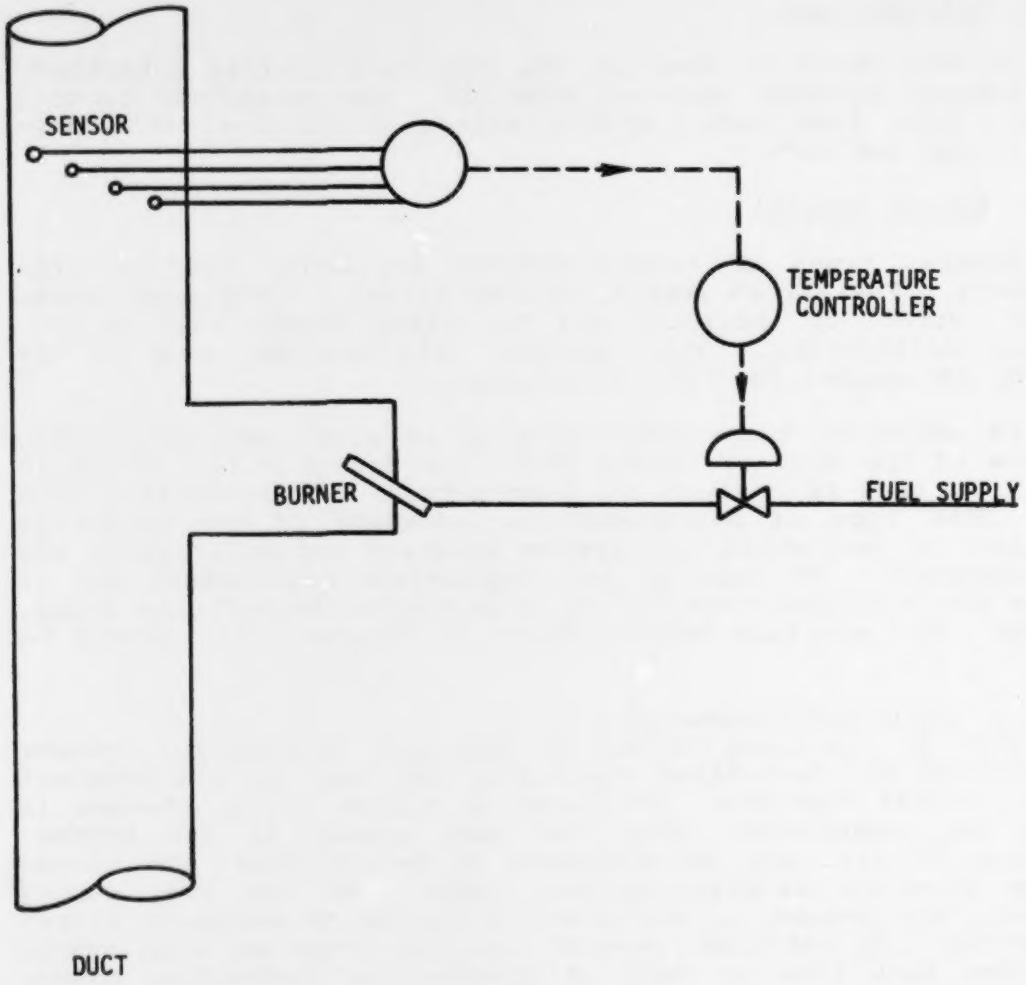

SENSOR
TEMPERATURE CONTROLLER
BURNER
FUEL SUPPLY
DUCT

Figure 3.3-1. Fuel-fired reheat control system.

Temperature control--One scheme for controlling the temperature of the hot water is shown in Figure 3.3-2a. In this case, steam is used to raise the temperature of the hot water as required by the temperature controller. Other variations of this system are possible.

The advantage of controlling the water temperature is that it results in a short time lag between gas flow fluctuations and the resulting change in heat input from the reheat medium, hot water. The disadvantage of this technique is that moderating the temperature may be hard to accomplish. Hot water (condensate) may be obtained from the turbine discharge.

Flow control--The other technique for moderating the flue gas temperature is shown in Figure 3.3-2b. In this system, the flow of water is changed by the temperature controller. As the velocity of water in the heat exchanger is increased, the outlet water temperature rises since the higher flow rate requires less temperature drop in the water to transfer the same amount of heat to the flue gas. This causes the log mean temperature difference to rise, which, in effect, raises the temperature of the flue gas. The advantage of this type of system is its simplicity. There is no major impact on the turbine system as long as the supply of hot water is greater than needed. The disadvantage of this system is the cost of the pump and the horsepower required to operate it. Energy requirements for pumping are fairly constant since the control valve absorbs the energy when the flow is reduced.

3.3.2.3 Steam Reheat--

To control the degree of flue gas reheat using a steam reheater coil, flow through the coil is changed. A steam reheater has two zones, one that has a high heat transfer rate where the steam is condensing, and a second that has a much lower rate where the hot condensate transfers heat to the flue gas. Care must be taken in the design of the coil to assure that the heat transfer to the gas is relatively uniform across the gas flow. If this is not accomplished, all the condensing sections of the steam coil will be on one side, and the rate of heat transfer will reach a maximum and then drop sharply. This phenomenon is called heat blinding; it may cause inadequate temperature rise in the flue gas. The advantage of this system is that the control requirements are well understood since steam flow control is quite common.

Steam is also utilized in reheater systems in which air is heated by the steam and then mixed with the flue gas.

3.3.3 Lime Feed Control

In a lime scrubber system, control of lime feed is absolutely essential. Lime feed rate is one of the factors that

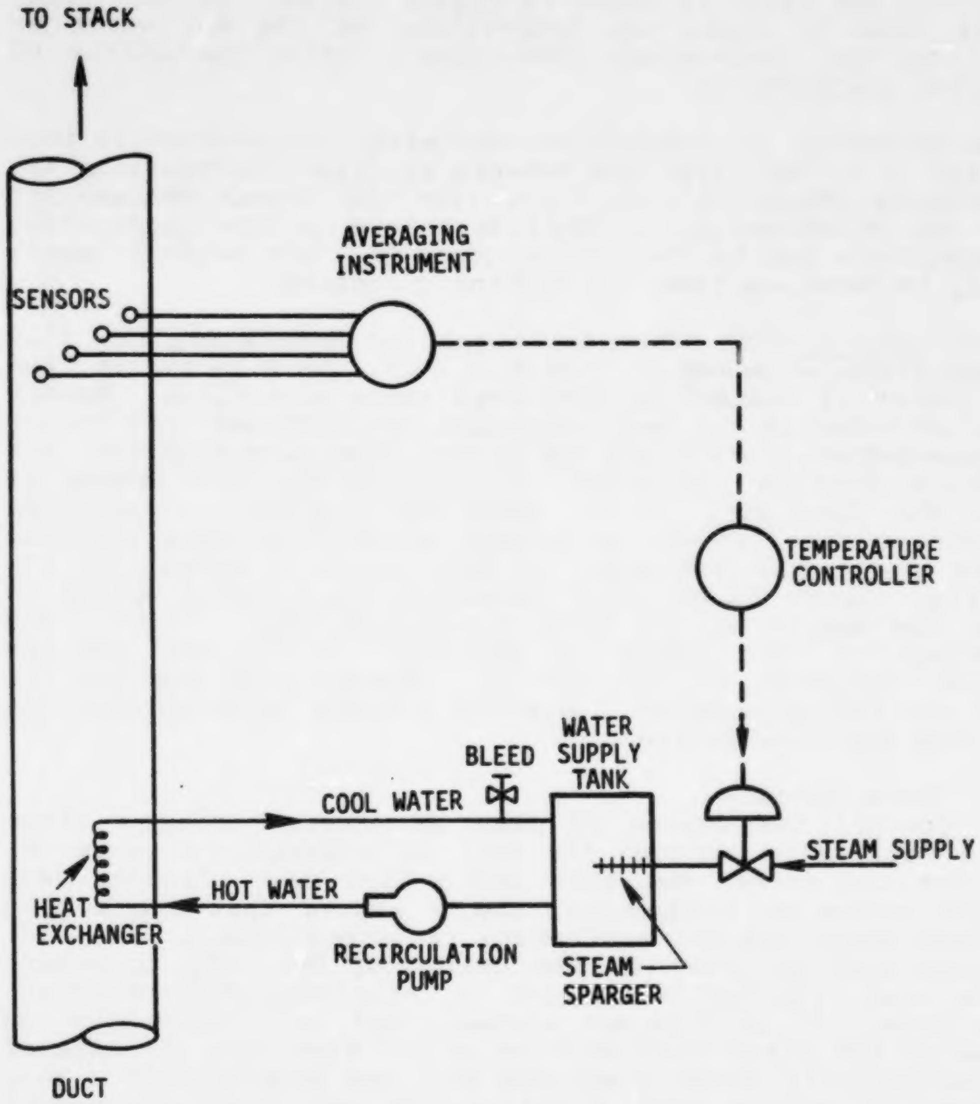

TO STACK
AVERAGING INSTRUMENT
SENSORS
TEMPERATURE CONTROLLER
WATER SUPPLY TANK
BLEED
COOL WATER
STEAM SUPPLY
HOT WATER
HEAT EXCHANGER
RECIRCULATION PUMP
STEAM SPARGER
DUCT

Figure 3.3-2a. Hot water reheat control system: steam raises hot water temperature.

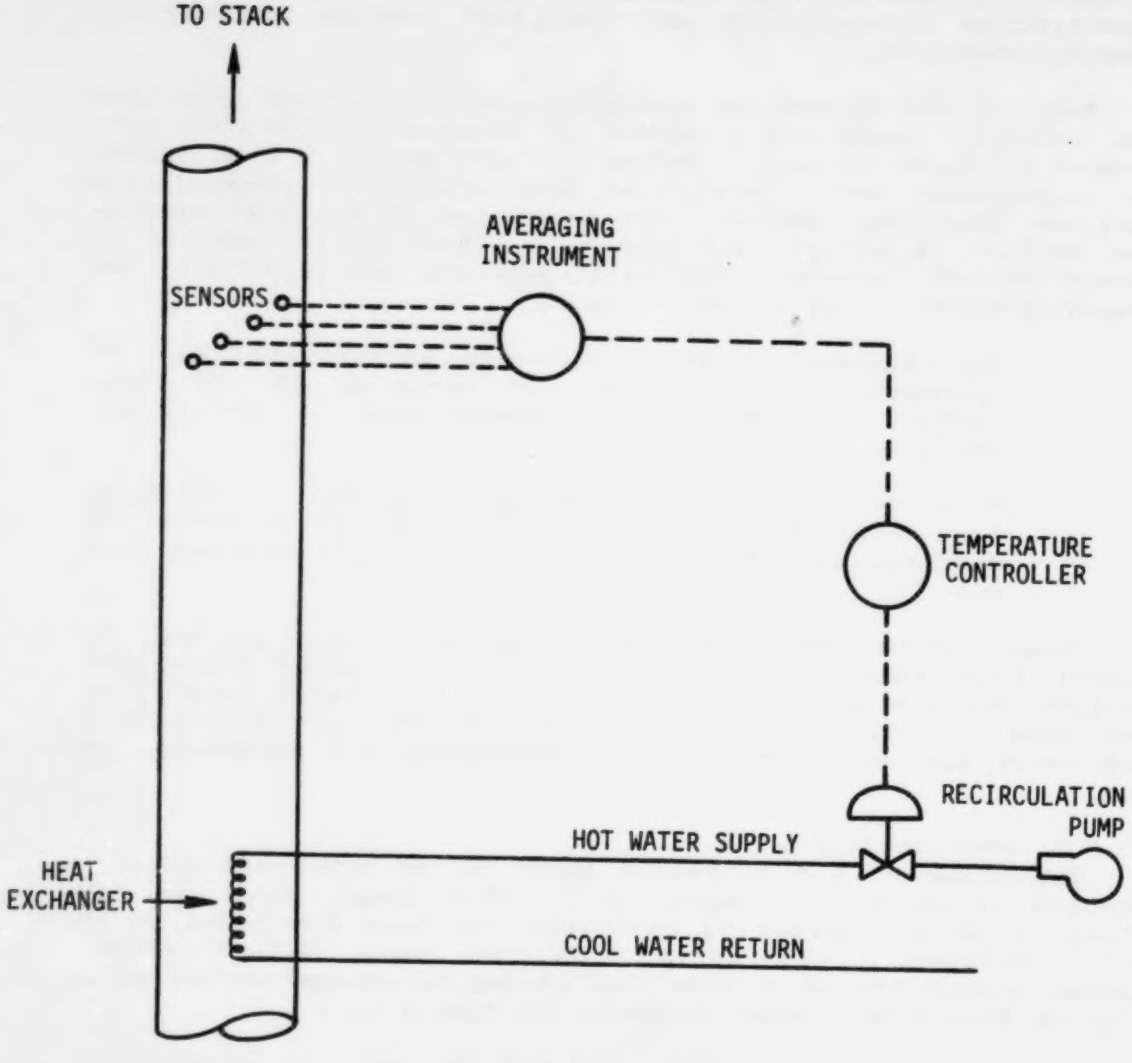

TO STACK
AVERAGING INSTRUMENT
SENSORS
TEMPERATURE CONTROLLER
RECIRCULATION PUMP
HOT WATER SUPPLY
HEAT EXCHANGER
COOL WATER RETURN

Figure 3.3-2b. Hot water reheat control system: flow of water charged by temperature controller.

determines the outlet SO_2 concentration in the flue gas. Proper pH control through proper lime addition can prevent scaling and reduce corrosion, thereby improving the mechanical performance of the scrubbing system.

All systems now operating control the lime feed rate with a feedback loop, and all use pH as the controlled variable. Most are unable to handle large changes in gas flow rate or inlet SO_2 concentration automatically and therefore require considerable operator attention.

Many of the systems in operation report problems with lime feed control. There are a number of reasons for the poor performance of these systems. Mechanical problems have been numerous, especially those created by poor design of pH-measuring electrode stations. Details are discussed in the Instrumentation Section (4.13) of this Data Book. From the standpoint of process control, however, the major problems are created by two characteristics of the process itself:

- The response of pH to a change in lime feed rate is extremely nonlinear, and the shape of the pH curve changes as the chemical composition of the slurry changes.

- By itself, pH is an inadequate variable on which to base lime feed rate. Optimal pH varies with the chemical composition of both the slurry and the flue gas.

These limitations necessitate complex control systems to control lime feed rate dependably. The following paragraphs describe the two process conditions that have major impacts on lime feed control. In addition, methods for controlling lime feed rates are shown with the disadvantages and advantages of each.

3.3.3.1 Nonlinearity--

The shape of the titration curve of an acid-base neutralization is shown in Figure 3.3-3. This graph shows the response of pH as increasing quantities of base are added to an acidic solution. The curve does not have uniform slope. Greater quantities of a base are needed to change the pH of a solution from 4 to 5 than to change it from 5 to 6.

A standard controller is a linear device. It is adjusted to add a certain quantity of lime to correct a pH change of a certain magnitude; if the change is doubled, the rate of lime addition is also doubled. This is not the best response for pH control.

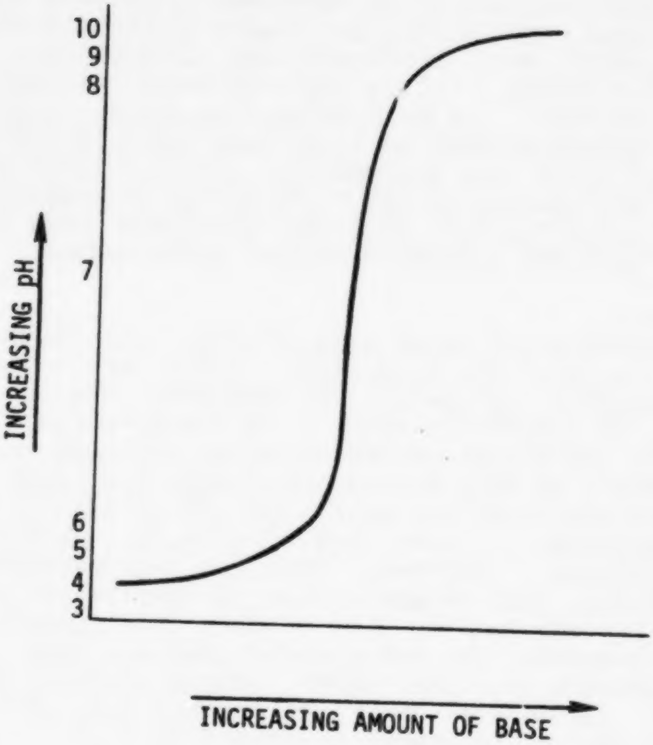


Figure 3.3-3. Shape of neutralization curve.

If the acid-base neutralization is buffered, as it is in a lime scrubber, the titration curve is slightly flatter though less regular. There are "plateaus" where the mixture absorbs quantities of lime, and there is little or no change in pH. As the degree of buffering changes, the shape of the curve changes. Buffered solution in a scrubber, however, is no more amenable to standard linear control than is an unbuffered pure solution.

During the last several years, nonlinear controllers specifically designed for control of pH have been produced by several manufacturers. These controllers partially correct the mismatch by supplying two bands with different amplifications. Within a pH band near the set point, little amplification of the controller output signal occurs. As pH change increases, larger amplification makes a larger change to lime feed rate to drive the pH back more rapidly into the acceptable range. Controllers of this type are in use in scrubbers. While not a complete answer to the lime feed rate control problem, they are more suited to this application than are standard linear instruments.

3.3.3.2 Time Lag--

Since the reaction of lime with acidic constituents in the scrubber slurry is not instantaneous, tanks are normally included in the process to hold the scrubber slurry and lime mixture from 5 to 15 minutes before it is recycled to the scrubbing vessels. The best-controlled scrubber systems use baffled or overflow chambers in the slurry recirculation tank. In some systems, the important control point for pH is the slurry as it is repumped; therefore, a time lag of several minutes is inherent in the process. However, this is not necessarily the case. At Conesville, for example, the pH sample is taken from the scrubber effluent before it reaches the reaction tank. Therefore, the response is relatively rapid. The return pH depends on the amount of lime added, which in turn depends on the amount of SO_2 to be absorbed. At Paddy's Run, for example, return pH is 9 to 10; at Shawnee, it is 6.5 to 7.5.

3.3.3.3 Simple pH Control--

As shown in Figure 3.3-4, pH can be used to control lime feed in a scrubbing system. The primary advantage of this system is that it is simple. In many systems, the scrubbing liquor has an ability to absorb sufficient SO_2 so that this type of control may be adequate. A major disadvantage is low lime utilization. In some cases the lime feed rate is set using a material balance at the highest SO_2 rate; therefore, the pH controller only detects major high and low SO_2 changes. In addition, major SO_2 variations in flue gas are only detected after impacts on scrubber chemistry, scaling, and corrosion. This disadvantage prevents consistent process control.

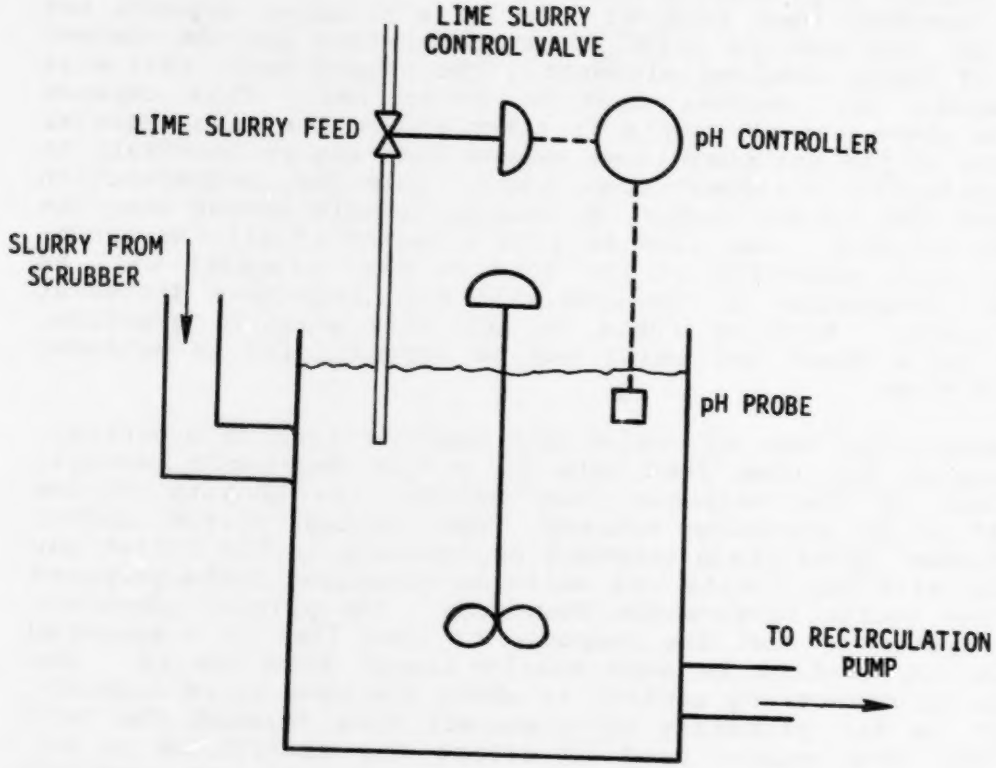

LIME SLURRY CONTROL VALVE
LIME SLURRY FEED
pH CONTROLLER
SLURRY FROM SCRUBBER
pH PROBE
TO RECIRCULATION PUMP

Figure 3.3-4. Simple pH control.

3.3.3.4 Cascade pH Control--

Several of the newer lime scrubbing FGD systems are being designed with either a closed- or an open-loop cascade control system (Figure 3.3-5). Two pH controllers are used. The lime feed pH is regulated by a secondary loop maintaining the pH in the lime slurry mix tank. The primary pH controller, measuring at the point where the recirculating slurry is returned to the absorber, readjusts the set point of the secondary controller to compensate for the varying offset. By greatly reducing time lag, control is significantly improved.

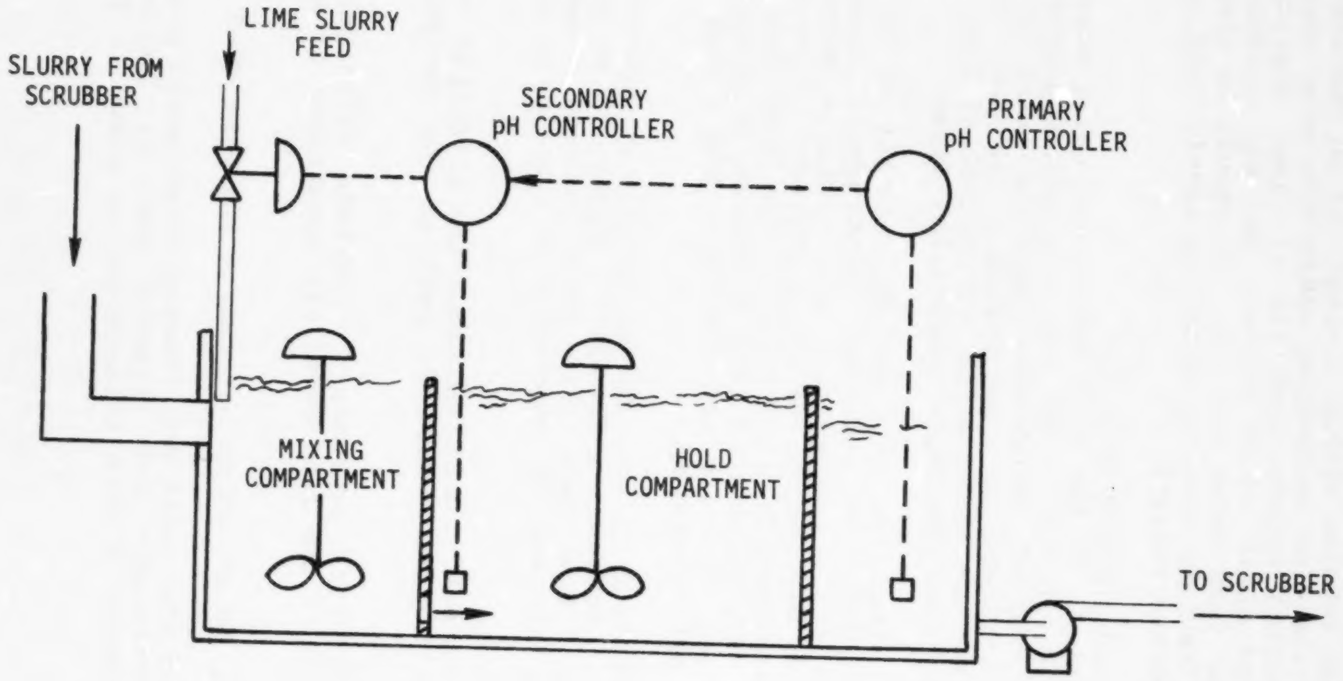
In some systems, the primary controller is open loop. Only a pH recorder is supplied, and the operator becomes the controller, periodically readjusting the secondary instrument.

3.3.3.5 Outlet SO_2 Feedback Control--

The optimal feed rate of lime to a scrubber depends not only on pH, but also on inlet SO_2 concentration and the concentration of other chemical elements. The pH set point that will give adquate SO_2 removal must be determined. This depends mainly on where the pH sample is taken and on the mass transfer capability of the scrubber (some excess lime may be necessary to offset inadequate scrubber capability). Inlet SO_2 concentration may affect the latter factor, by requiring more excess when the inlet SO_2 is high. Gas flow is also a factor if all the scrubbers are left operating at low load so mass transfer will be improved. Magnesium in the lime will also require a different pH set point. Most of these do not vary much in practice, however, so a given set point may be adequate for an extended period of time.

However, the use of outlet SO_2 concentration as a controlled variable for lime feed rate is a more desirable concept, since this is the variable that defines the quality of the "product" of the scrubbing process. The eventual direct control of a scrubber to maintain constant SO_2 content in the outlet gas is likely with SO_2 limits and emission averaging times proposed in the New Source Performance Standards. The primary advantage of this system is that the response of lime feed to a measured error in SO_2 content is more nearly linear than the pH. The time lag for direct SO_2 control is about the same as pH control, since it is set primarily by transport time through the hold tank. The loop sensor used in direct SO_2 control is an SO_2 analyzer. The performance of these instruments and sampling trains in some of the newer lime scrubbers has been rather poor.

Application of this control method, however, will require pH control. Although pH can be varied to obtain the best SO_2 removal, it must be maintained within a range that will cause neither corrosion nor scale formation. Instrumentation can be



LIME SLURRY FEED
SLURRY FROM SCRUBBER
SECONDARY pH CONTROLLER
PRIMARY pH CONTROLLER
MIXING COMPARTMENT
HOLD COMPARTMENT
TO SCRUBBER

Figure 3.3-5. Cascade pH control.

used to limit a feedback loop, as shown in Figure 3.3-6. The time-synchronized recorder charts show the action that would be expected. The lime feed rate would be controlled by the SO_2 loop, providing the pH remains within limits. If pH reaches its high limit, the high-limit pH controller would take over control of the valve, preventing further addition of lime. Similarly, the low-limit pH controller would prevent the SO_2 controller from closing the lime feed valve too far. It should be greatly emphasized that SO_2 feedback control cannot be widely used until wet SO_2 analyzers operate reliably.

3.3.3.6 Inlet SO_2 Feed-forward Control--

Feed-forward control of the lime feed rate, using measurement of the inlet SO_2 concentration, has also been suggested as a possible means to control improvement, and the basic instrumentation has been included in some scrubber designs. Feed-forward systems are the preferred method of control of lime feed rate in scrubbers in other countries, especially Japan.

In this system, the flow rate and SO_2 content of the gas entering the scrubber would be measured. Instruments measuring the SO_2 content of a dry gas have shown more reliable operation in the field than have wet gas stream SO_2 analyzers. From these measurements, an instrumented calculation of the mass flow rate of SO_2 can be made. The lime feed rate should be in proportion to the quantity of SO_2 entering the scrubber, and a feed rate controller would be set accordingly.

The primary advantage of this system is that it responds to SO_2 and gas changes. However, although it appears to be simple and basically sound, it suffers from three process disadvantages, which may or may not be important in a specific application:

- Time lag is not eliminated since the principal lag is in the hold tank, which is part of the manipulated stream.
- Proper operation presumes a constant efficiency of utilization of the lime under all conditions of operation.
- Outlet SO_2 emissions do not change the lime feed rate.

Feed forward of the inlet SO_2 concentration would probably operate well if "trimmed," but trimming must be limited by slurry pH. A schematic of this arrangement is shown in Figure 3.3-7.

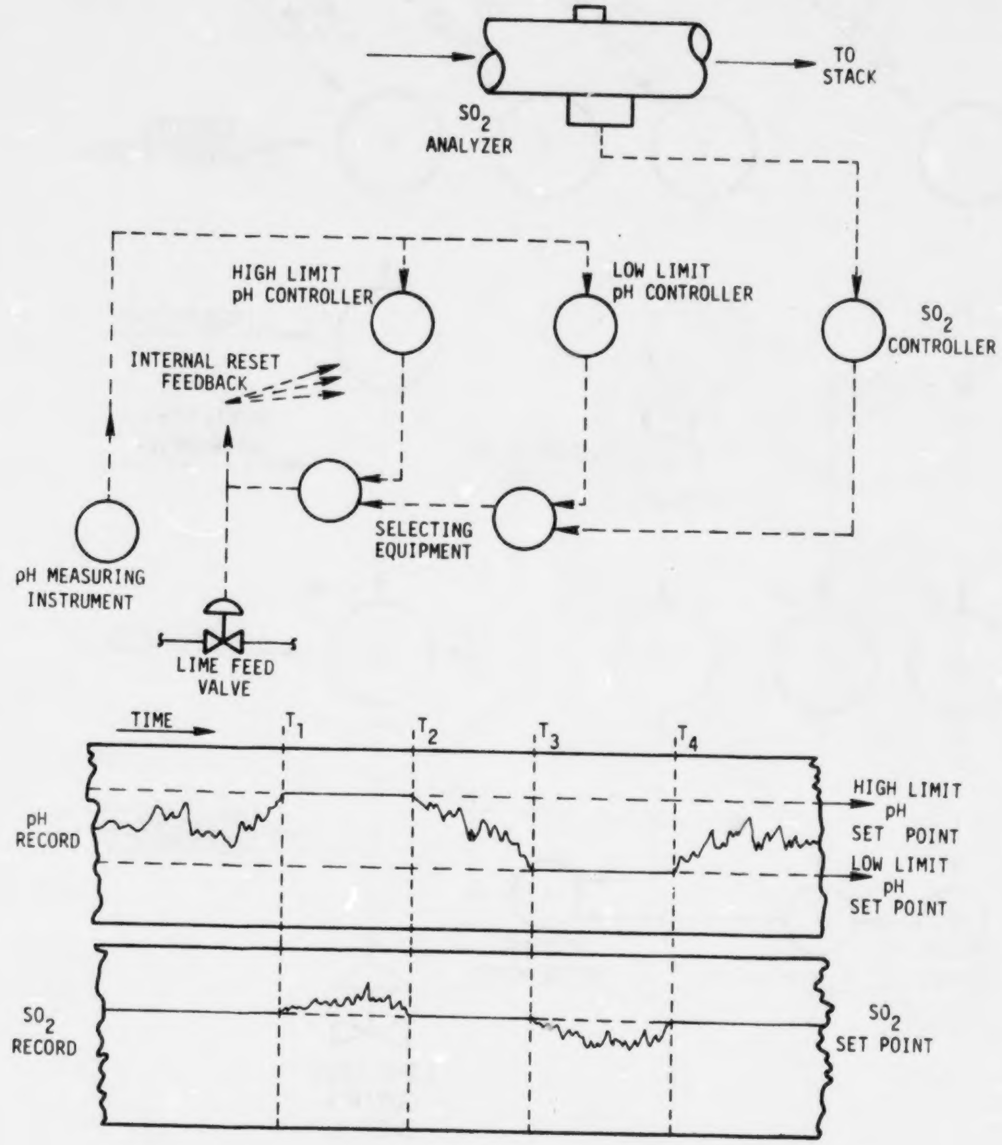

TO STACK
SO_2 ANALYZER
HIGH LIMIT pH CONTROLLER
LOW LIMIT pH CONTROLLER
SO_2 CONTROLLER
INTERNAL RESET FEEDBACK
SELECTING EQUIPMENT
pH MEASURING INSTRUMENT
LIME FEED VALVE
TIME
T_1
T_2
T_3
T_4
pH RECORD
HIGH LIMIT pH SET POINT
LOW LIMIT pH SET POINT
SO_2 RECORD
SO_2 SET POINT

Figure 3.3-6. Outlet SO_2 feedback control (limited).

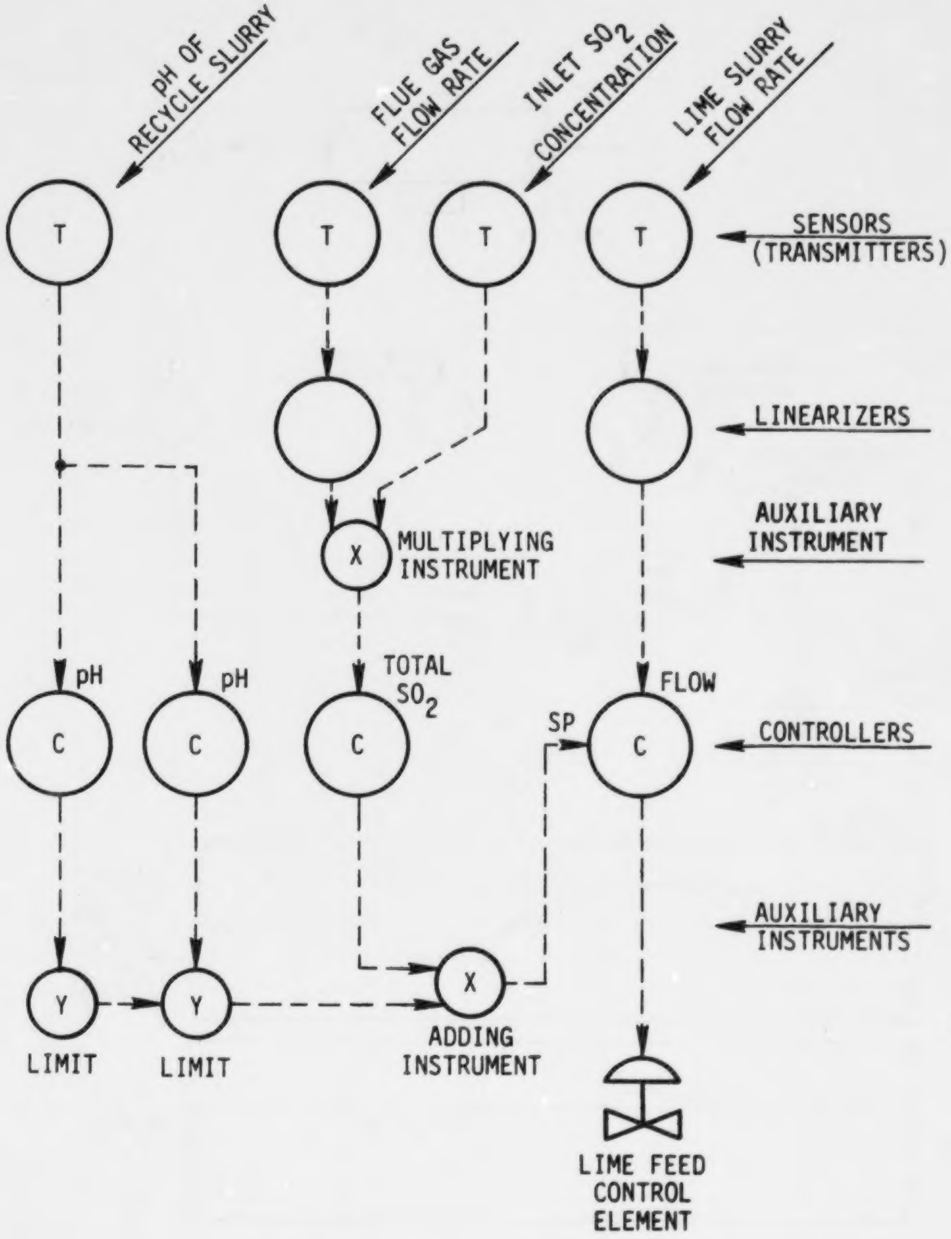

pH OF RECYCLE SLURRY
FLUE GAS FLOW RATE
INLET SO_2 CONCENTRATION
LIME SLURRY FLOW RATE
T
T
T
T
SENSORS (TRANSMITTERS)
LINEARIZERS
AUXILIARY INSTRUMENT
X
MULTIPLYING INSTRUMENT
pH
pH
TOTAL SO_2
FLOW
SP
C
C
C
C
CONTROLLERS
AUXILIARY INSTRUMENTS
Y
Y
X
LIMIT
LIMIT
ADDING INSTRUMENT
LIME FEED CONTROL ELEMENT

Figure 3.3-7. Inlet SO_2 feed-forward control.

3.3.3.7 Conclusions--

If the operability of wet SO_2 analyzers improves, they should be added to the system. New control systems should have provisions for future feedback control. With the emphasis on stricter emission limits and shorter emission averaging times, outlet SO_2 emissions will be monitored by the EPA. The incentive to develop workable SO_2 monitoring equipment will exist. However, to date, simple pH control has proved to be acceptable, and it reduces the amount of instrumentation that can cause problems. It is possible that such control causes more lime usage than is absolutely necessary, but this hypothesis is difficult to prove. In any event, the excess merely gives higher SO_2 removal than the regulation requires.

3.3.4 Slurry Solids Control

In a lime slurry system, there are three areas where the solids content of the slurry is controlled: the lime slurry feed, the absorber recirculation loop, and the thickener underflow. Although solids content can vary without being critical to the operation of the absorber, the use of a consistent lime slurry can reduce plugging and deposits in the absorber, reduce waste volume from the thickener, and improve pH control.

To avoid fouling of the sensor, each control area uses indirect measurements of the slurry density by magnetic and nuclear density sensors. These devices measure the absorptive properties of the slurry and correlate them to the solids content of the slurry. Although the correlation is not exact, this type of measurement has proved highly accurate for most applications.

3.3.4.1 Lime Slurry Feed Control--

As shown in Figure 3.3-8, lime slurry concentration can be controlled by measuring the density of the slurry leaving the stabilization tank. A simple feedback system uses freshwater makeup or thickener overflow to reduce or increase the solids content as required. The advantage of this system is simplicity; the disadvantage is the control time lag.

If a gravimetric feeder is used for lime feed, then a feed-forward system with slurry density feedback trim should be used. This system is illustrated in Figure 3.3-9. The advantage of this system is more uniform control; the disadvantage is system complexity and added cost.

3.3.4.2 Absorber/Scrubber Solids Control--

To prevent a buildup of the absorption products, the solids content of the recirculation slurry must be controlled. Although there are several theories on concentrated slurries and diluted slurries, which will not be discussed here, the solids

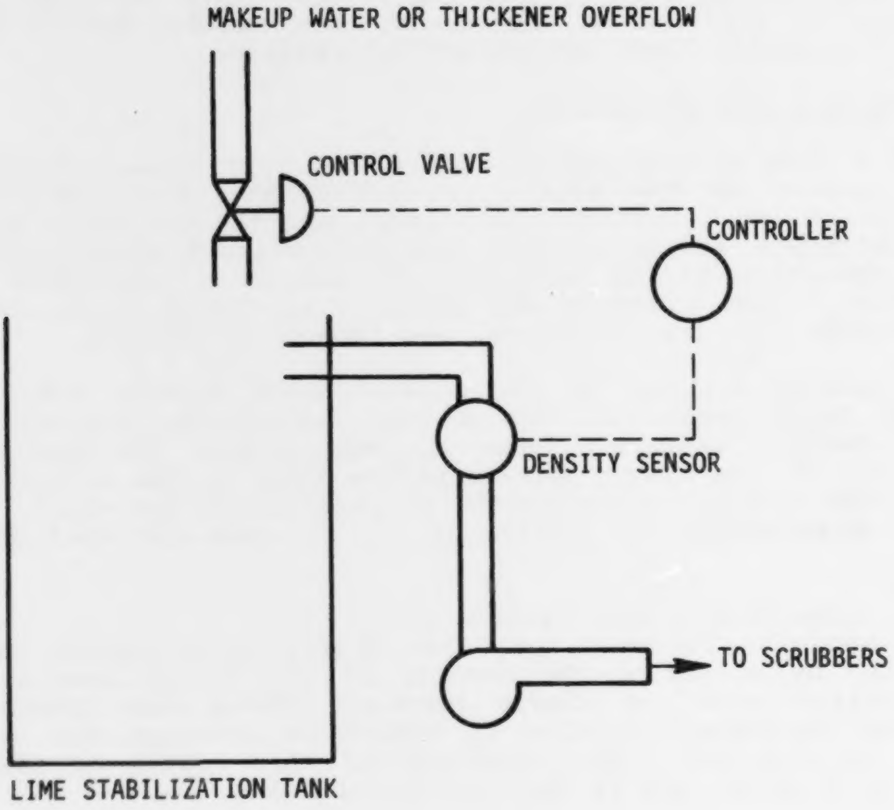

MAKEUP WATER OR THICKENER OVERFLOW
CONTROL VALVE
CONTROLLER
DENSITY SENSOR
TO SCRUBBERS
LIME STABILIZATION TANK

Figure 3.3-8. Lime slurry solids control: density feedback.

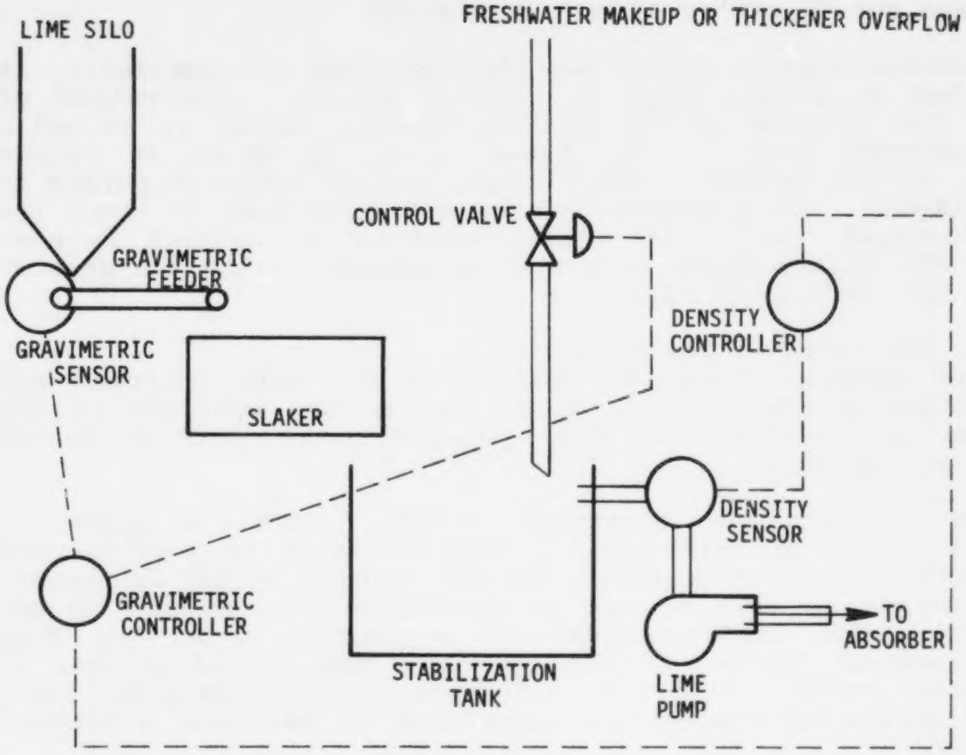

LIME SILO
FRESHWATER MAKEUP OR THICKENER OVERFLOW
CONTROL VALVE
GRAVIMETRIC FEEDER
DENSITY CONTROLLER
GRAVIMETRIC SENSOR
SLAKER
DENSITY SENSOR
GRAVIMETRIC CONTROLLER
TO ABSORBER
STABILIZATION TANK
LIME PUMP

Figure 3.3-9. Lime slurry solids content: feed-forward control.

content must be controlled to minimize plugging and buildup and reduce the load on solids concentrating equipment such as the thickener. The simplest system for controlling the solids content in the absorber loop is a density sensor and a bleed to the thickener or pond. In this system, which is shown in Figure 3.3-10, a level controller adds more fresh-water or thickener overflow as the slurry is bled off. This dilutes the slurry to the required extent. As the solids content decreases, water makeup and the thickener bleed are reduced.

Although such a system has the advantage of simplicity, it is limited by severe wear on control valves. One method of solving the problem of the eroding control valves is to add a variable-speed pump to the bleed line, as shown in Figure 3.3-11. As the solids content rises, solids would be purged to the thickener, and additional water would be used to lower the solids content. With this system good solids control is possible. The disadvantages are system complexity and the greater cost of the additional pumps.

3.3.4.3 Thickener Solids Control--

This section discusses techniques for both constant and intermittent solids control in the outlet and overflow of the thickener when the feed to the thickener varies both in solids content and quantity.

One approach for thickener solids control is shown in Figure 3.3-12. In this case, a control valve is used to vary the underflow rate to maintain solids content in the thickener. The advantage of this system is uniform solids content in the underflow. The disadvantages are nonuniform underflow flow rates, lack of control of the overflow, and excessive wear of the control valve. A no-flow situation is not tolerable, and a certain amount of control is sacrificed to maintain a minimum underflow.

Another method of solids control is shown in Figure 3.3-13. In this system, the underflow is constantly recycled to the thickener with a bleed stream going to the downstream sludge treatment. The advantage of this system is uniform pump operation and more uniform solids level in the underflow without the problems of maintaining a minimum underflow. However, again a control value is required, which will be worn by abrasive slurry. Other disadvantages of the system are the need for an oversized pump and the pump's excessive energy requirements.

3.3.4.4 Flocculant Control--

Provisions should be made in the solids control system for flocculant addition. Although it is expensive to allow for some oversize in thickeners, thickener optimization is difficult with

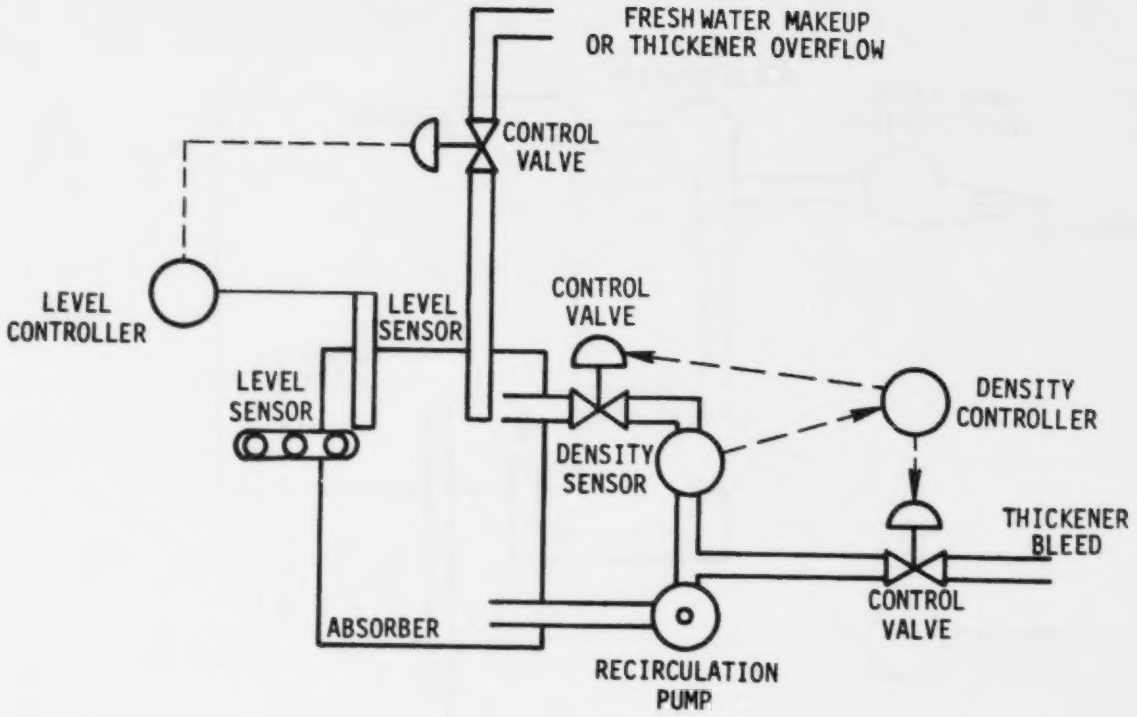

FRESHWATER MAKEUP
OR THICKENER OVERFLOW
CONTROL VALVE
LEVEL CONTROLLER
LEVEL SENSOR
LEVEL SENSOR
CONTROL VALVE
DENSITY CONTROLLER
DENSITY SENSOR
THICKENER BLEED
CONTROL VALVE
ABSORBER
RECIRCULATION PUMP

Figure 3.3-10. Absorber solids content: thickener bleed control.

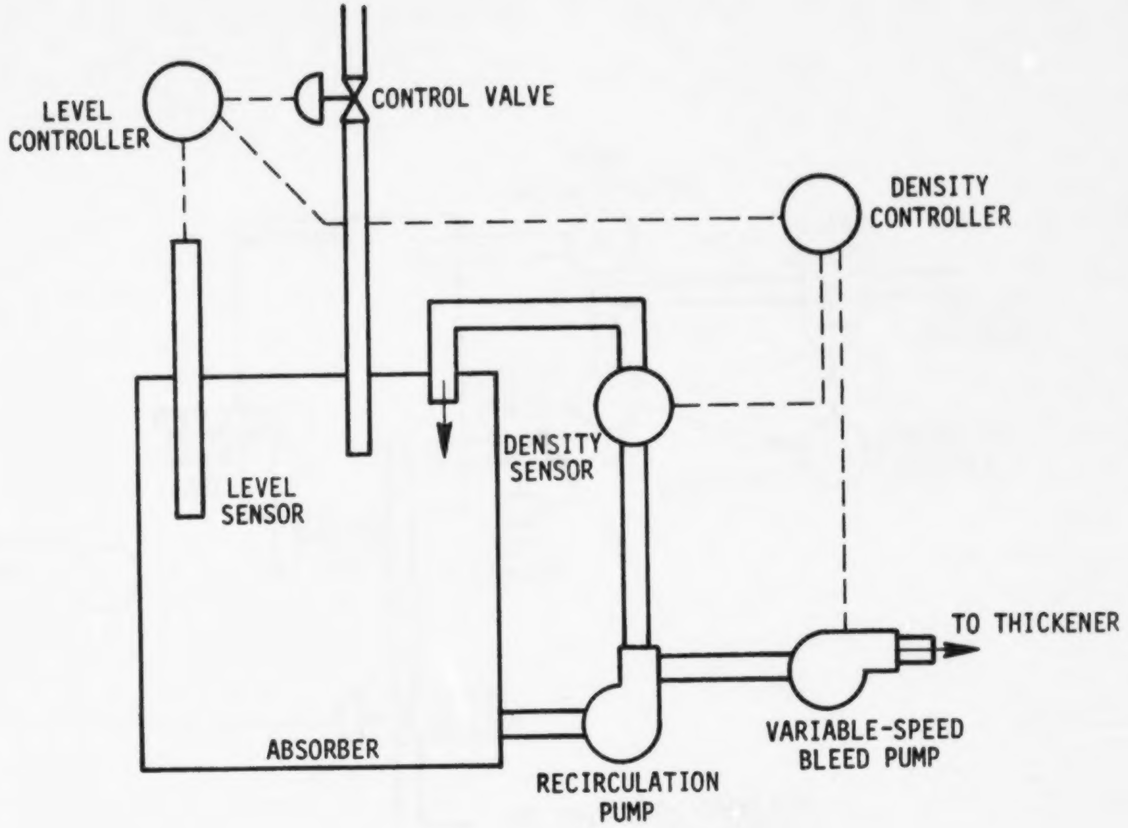

LEVEL CONTROLLER
CONTROL VALVE
DENSITY CONTROLLER
LEVEL SENSOR
DENSITY SENSOR
TO THICKENER
ABSORBER
RECIRCULATION PUMP
VARIABLE-SPEED BLEED PUMP

Figure 3.3-11. Absorber solids content: variable-speed pump control.

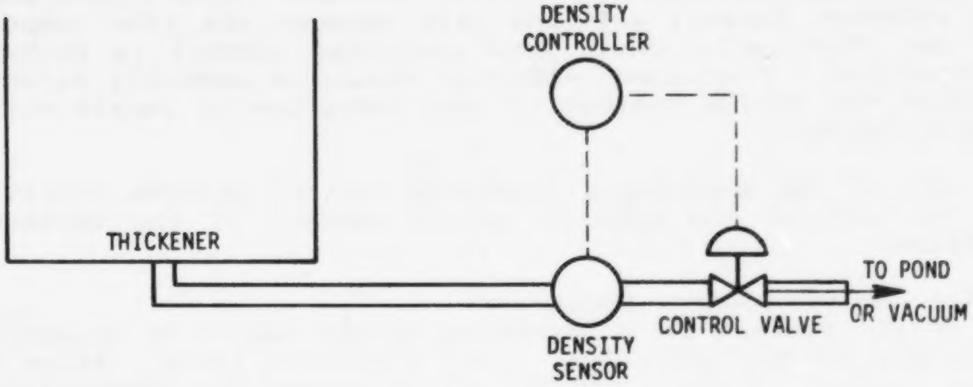

DENSITY
CONTROLLER
THICKENER
TO POND
OR VACUUM
CONTROL VALVE
DENSITY
SENSOR

Figure 3.3-12. Thickener solids content:
underflow control flow.

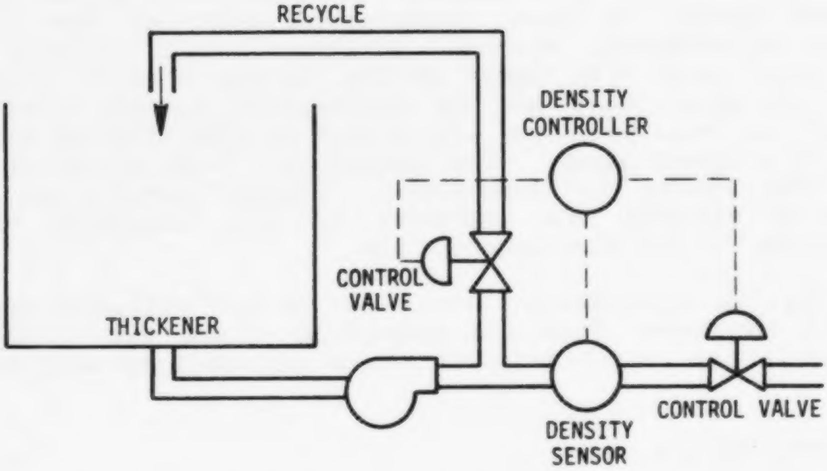

RECYCLE
DENSITY
CONTROLLER
CONTROL
VALVE
THICKENER
CONTROL VALVE
DENSITY
SENSOR

Figure 3.3-13. Thickener solids content:
recycle control.

the current state of the art. Flocculants can be used to solve solids content problems in systems in which the thickener is undersized or the chemical properties of the coal and lime change and cause thickening problems. A typical flocculant control system is shown in Figure 3.3-14. The flocculant feed is varied with the underflow solids content. This system has a slow response because settling rate changes are slow compared with gas flow variations. True regulated control is probably not possible. Flocculant addition should be manually adjusted to allow the solids content of the underflow to remain within certain limits.

One of the previously discussed control methods should be used to control the precise solids content of the thickener underflow.

3.3.4.5 Solids Control Summary--

Solids content in a scrubbing system cannot be controlled adequately by the individual loops discussed above. Since the solids content of the scrubber and thickener are interrelated, the solids should be controlled as a system. In a plant in which the water loop is closed, a system such as that shown in Figure 3.3-15 is feasible. In this system, the bleed from the absorber is restricted with an orifice plate, the thickener acts as a surge for the variations in solids loading on the system, and a variable-speed pump is used to control the solids content of the thickener underflow.

Although the system has numerous limitations, which have been discussed above, it does incorporate most of the best features of a satisfactory system. Although solids content in the scrubber will vary with large shifts in gas flow or composition, some variation will not be detrimental to SO_2 absorption. Most of the wear problems are solved by the orifice plate and the variable-speed pump. The danger of line plugging is solved since the system is continuous. Manual recycle may be required during startup and shutdown of the thickener when solids production in the absorber is low.

An alternative arrangement would be to use variable-speed pumps for both thickener feed and underflow, since the slightly increased cost would definitely increase reliability and controllability.

3.3.5 Gas Flow Control

A lime scrubbing system usually needs distribution of stack gas flow. Gas volume is controlled by the boiler. The scrubbing system must respond and not affect boiler operation. If multiple scrubbing units are used, a dependable system to balance gas flow rates in the parallel units must be provided. In

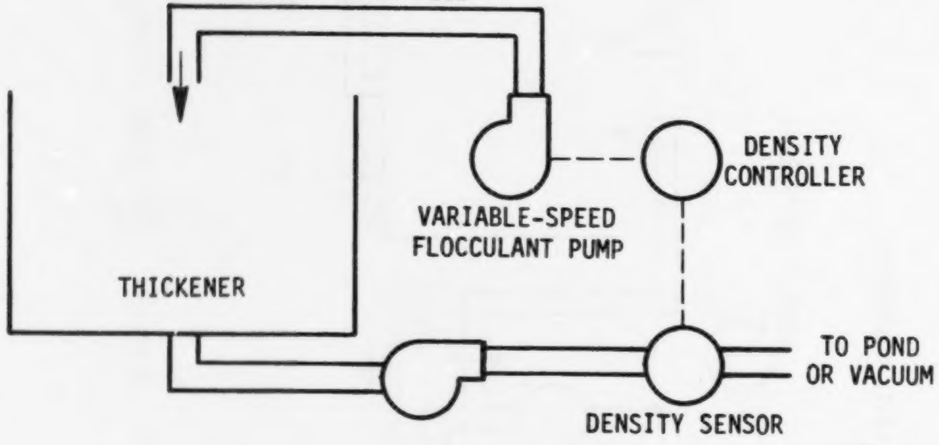

FLOCCULANT FEED
DENSITY CONTROLLER
VARIABLE-SPEED FLOCCULANT PUMP
THICKENER
TO POND OR VACUUM
DENSITY SENSOR

Figure 3.3-14. Thickener solids content: flocculant control.

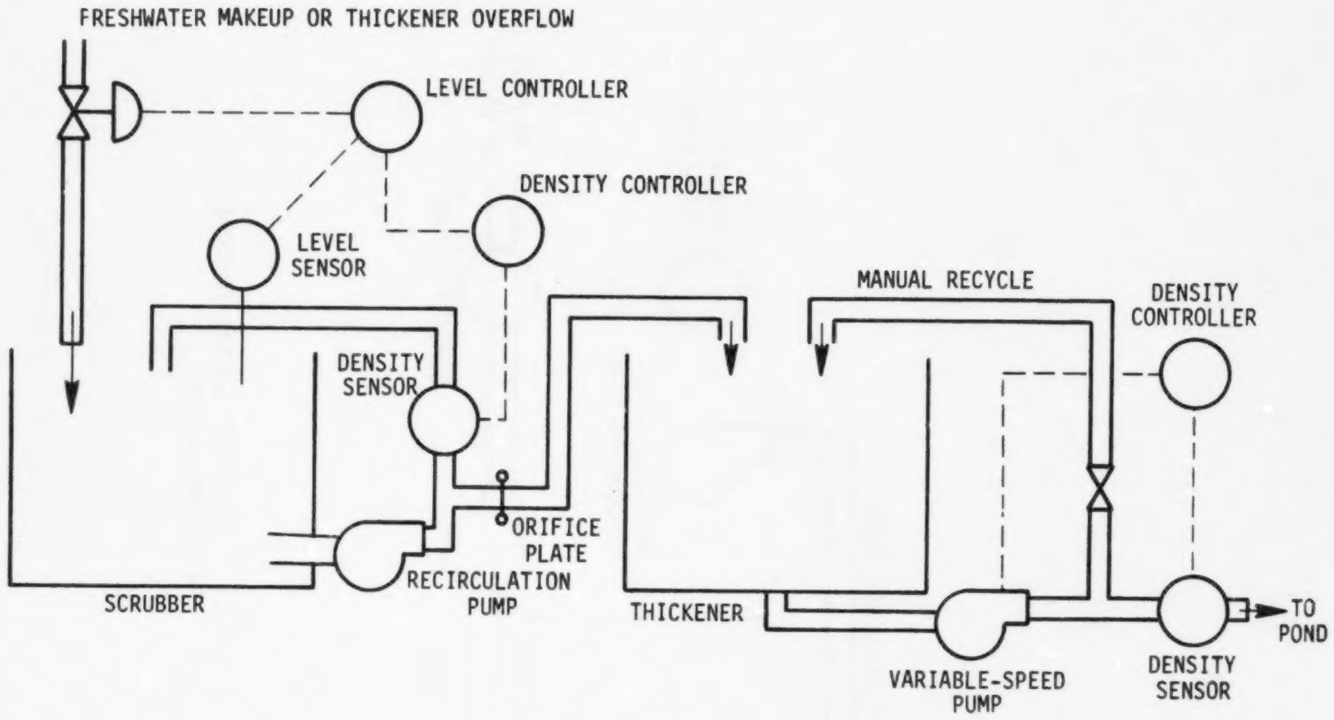

FRESHWATER MAKEUP OR THICKENER OVERFLOW
LEVEL CONTROLLER
DENSITY CONTROLLER
LEVEL SENSOR
DENSITY SENSOR
ORIFICE PLATE
RECIRCULATION PUMP
SCRUBBER
THICKENER
MANUAL RECYCLE
DENSITY CONTROLLER
VARIABLE-SPEED PUMP
DENSITY SENSOR
TO POND

Figure 3.3-15. Absorber: thickener solids control system.

a retrofit installation of a scrubbing system, coordination between the boiler and scrubbing controls is necessary. Even in new units, the control coordination used for retrofit scrubbers is needed, since the boiler and the scrubber are most often designed as separate units and frequently have separate control rooms.

3.3.5.1 Pressure Control--

The simplest method of controlling gas volume through each scrubbing vessel is the use of pressure control. A constant pressure is maintained at the inlet of the absorber. This pressure is designed so that it does not impair the operation of the boiler by increasing the back pressure on the induced-draft fans of the boiler.

It has been demonstrated that simple feedback control, as shown in Figure 3.3-16, responds too slowly to maintain an adequately consistent pressure. A surge of pressure occurs with each change of boiler firing rate. A connection from the boiler control system is necessary, usually in the form of a feed-forward signal from the boiler combustion controls. The basic agreement is shown in Figure 3.3-17. Feed forward alone is insufficient. However, since no two fans or dampers will respond identically, feedback correction is necessary to prevent variations in pressure with changes in load. The instrumentation is similar to that used to balance the firing rate of parallel boilers.

3.3.5.2 Flow Control--

In multiple module scrubbing systems, it would be helpful to control the gas volume to each scrubbing module precisely. This requires one fan per module. However, flow is difficult to measure because of nonisokinetic flows in short duct runs. Long duct runs, which achieve the isokinetic conditions, are not economical. A possible system for flow control is shown in Figure 3.3-18. Because of the inaccuracies of flow measurement, the damper control is tripped with pressure control. Boiler feed-forward control is also fed into the system. The advantage of this system is that the flow rates for each module can be accurately controlled. The disadvantages of this system are complexity and flow measurement inaccuracy. Precise flow rates through each scrubber module are not required if the system can meet the removal efficiency at full load. At lower gas loads, excess SO_2 would be removed. Properly implemented, such a system would allow some of the modules to be baseloaded and others to vary according to changes in boiler firing.

3.3.5.3 Boiler Safety--

The most difficult problems of gas flow control arise in the protection of the boiler-scrubber system from explosion or

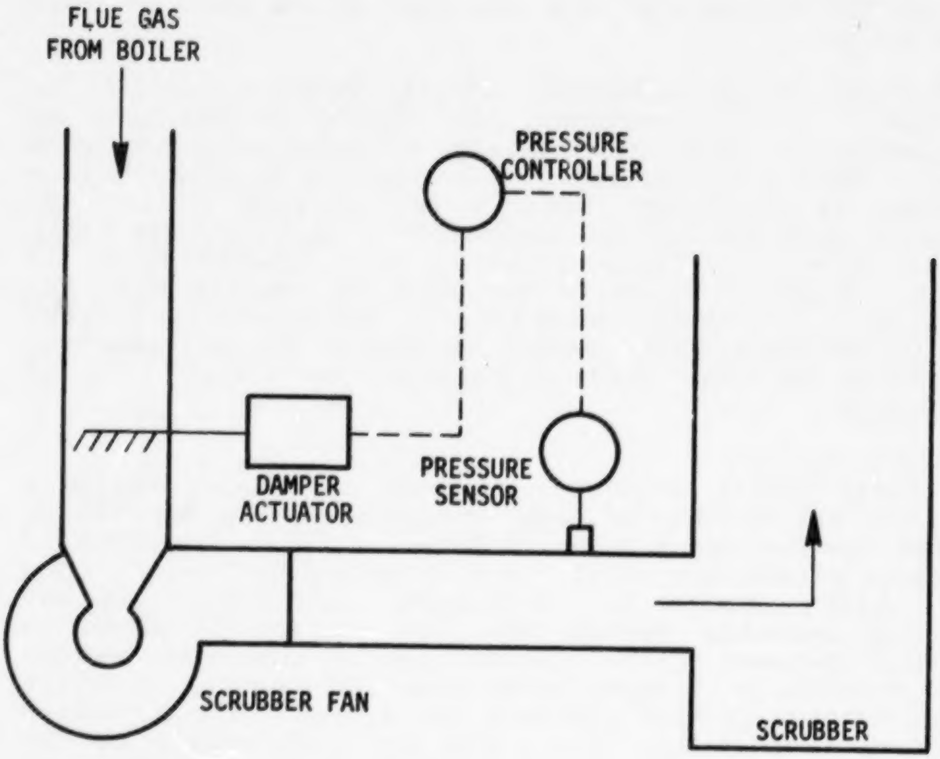

FLUE GAS
FROM BOILER
PRESSURE
CONTROLLER
DAMPER
ACTUATOR
PRESSURE
SENSOR
SCRUBBER FAN
SCRUBBER

Figure 3.3-16. Simple pressure control.

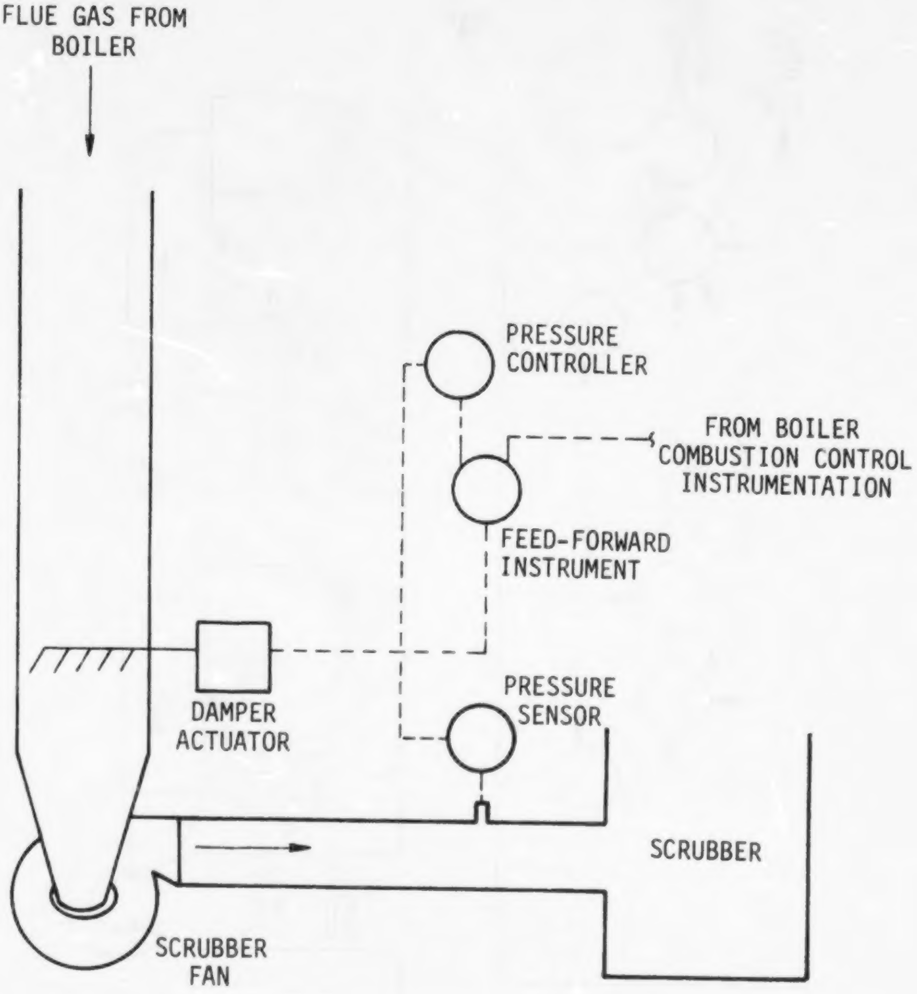

FLUE GAS FROM
BOILER
PRESSURE
CONTROLLER
FROM BOILER
COMBUSTION CONTROL
INSTRUMENTATION
FEED-FORWARD
INSTRUMENT
DAMPER
ACTUATOR
PRESSURE
SENSOR
SCRUBBER
SCRUBBER
FAN

Figure 3.3-17. Basic fan control subsystem.

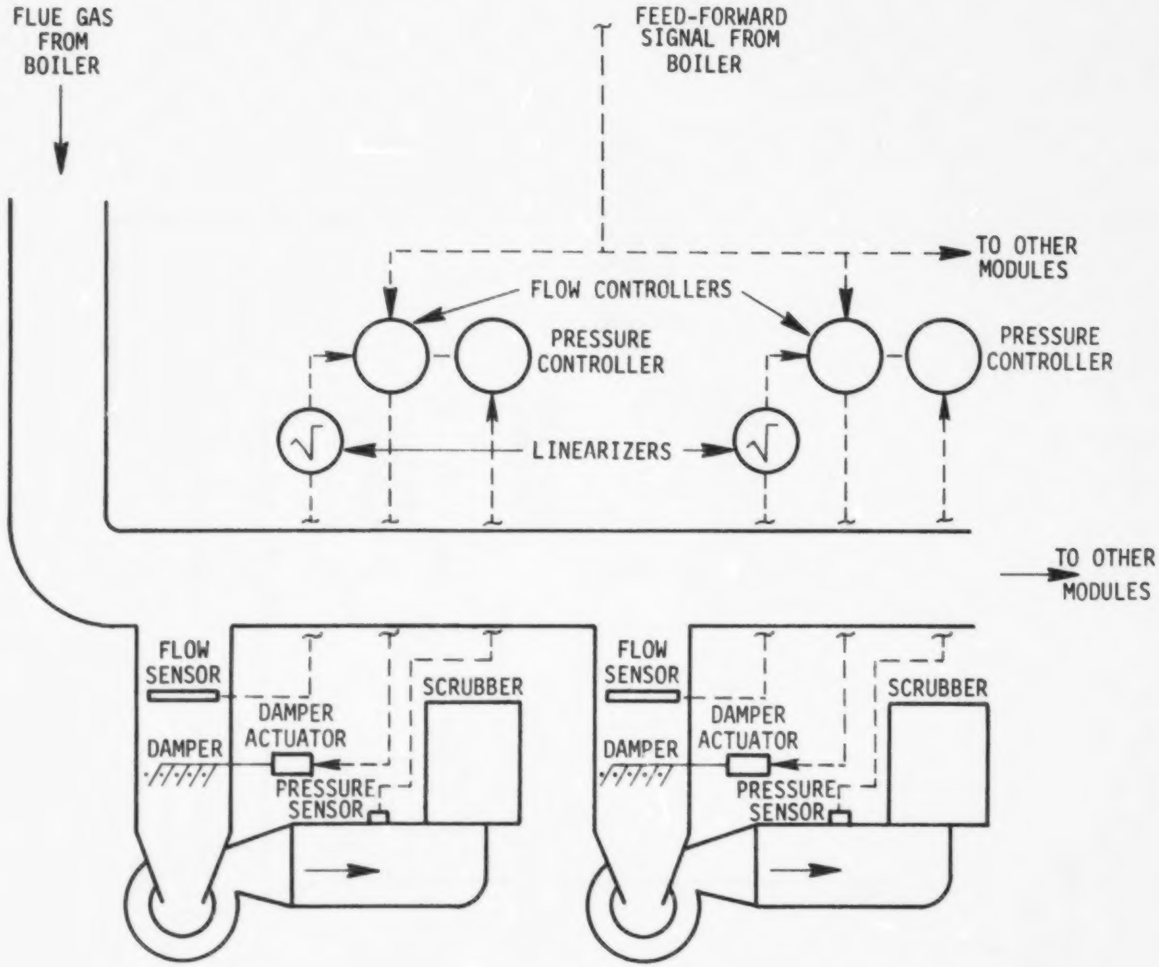

FLUE GAS FROM BOILER
FEED-FORWARD SIGNAL FROM BOILER
TO OTHER MODULES
FLOW CONTROLLERS
PRESSURE CONTROLLER
PRESSURE CONTROLLER
LINEARIZERS
TO OTHER MODULES
FLOW SENSOR
DAMPER ACTUATOR
DAMPER
PRESSURE SENSOR
SCRUBBER
FLOW SENSOR
DAMPER ACTUATOR
DAMPER
PRESSURE SENSOR
SCRUBBER

Figure 3.3-18. Module load balancing control.

implosion damage on trip-out of the boiler or on loss of a scrubber fan. When the boiler shuts down, there is either a sudden increase or decrease in gas flow rate, depending on the safety requirements of the boiler. Although interlocks will be used to achieve simultaneous shutdown of the boiler and the scrubber, pressure or vacuum surge can develop in the boiler and duct work if the dynamic response to this condition is unfavorable. Similarly, loss of a scrubber fan will produce a pressure surge in the opposite direction that will trip the boiler, but may also create potentially damaging surges.

If only part of the flue gas is passed through the scrubber and the remainder is bypassed through a damper, connection of the bypass damper and the scrubber fans to the boiler flame safeguard system is an acceptable solution. In the event of an emergency boiler shutdown, the scrubber fan is shut down and the damper is opened. If the scrubber fan fails, the damper is opened and an operator can conduct a more orderly shutdown of the boiler. Guidelines for this interconnection are being prepared by insurance standards organizations.

If the scrubber is not bypassed, however, the solution is much more complex. It has been found that conventional steady-state engineering analysis is inadequate to deal with this problem. Unusual flow conditions are created by flame collapse on unit shutdown, which can reverse flue gas flow direction and cause substantial implosion damage if outside air is not admitted into the unit. At the present time, each scrubber installation requires individual mathematical dynamic simulation studies to predict the effect of boiler failures and to aid in the design of dampers and interlocked trip sequences to reduce the possibility of boiler damage.

3.3.5.4 Fan Control--

Another possible method of flow control through individual modules is the use of variable-speed fans. A typical control loop is shown as Figure 3.3-19. This system uses the pressure at the scrubber inlet and a feed-forward signal to regulate fan speed. The advantages of this system include some reduction in energy consumption in the fan and better flow control than simple pressure control allows. The disadvantages include slow control response and higher capital costs. The slow response is due to the inertial of a large fan, which responds slowly to control signals.

There have been wide differences in fan location among operating lime scrubbers. Individual fans have been provided with each module, but in some units one fan serves several modules. Fans have been located upstream and downstream from the scrubber and also between the scrubbing modules.

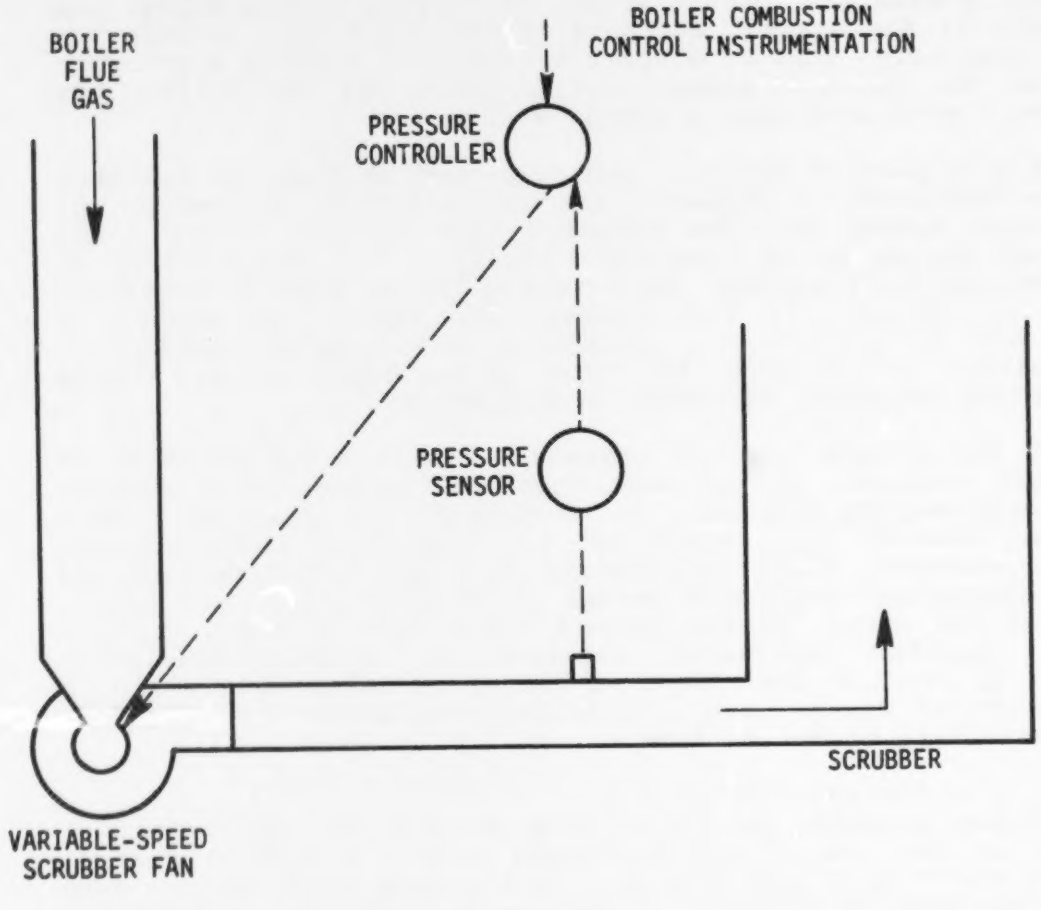

BOILER FLUE GAS
BOILER COMBUSTION CONTROL INSTRUMENTATION
PRESSURE CONTROLLER
PRESSURE SENSOR
SCRUBBER
VARIABLE-SPEED SCRUBBER FAN

Figure 3.3-19. Flue gas flow: fan control.

BIBLIOGRAPHY

Athans, M., and P. Falb. Optimal Controls. McGraw-Hill, New York, 1966.

Del Toro, V., and S. Parker. Principles of Control Systems Engineering. McGraw-Hill, New York, 1960.

Doennebrink, F., and J. Russell. LEM Stabilization and Control System. AIAA Guidance and Control Conference, August 1965.

Dorf, R.C. Modern Control Systems. Addison-Wesley Publishing Co., Reading, Massachusetts, 1966.

Dorf, R.C. Time-Domain Analysis and Design of Control System. Addison-Wesley, Reading, Massachusetts, 1965.

Franklin, G. Introduction to Modern Control Theory. Holden-Day, San Francisco, 1967.

Kuo, B.C. Automatic Control Systems. Prentice-Hall, Englewood Cliffs, New Jersey, 1962.

Lime/Limestone Scrubber Operation and Control Study. EPRI (RP630-2), April 1978.

Marks, L.S. Standard Handbook for Mechanical Engineering. McGraw-Hill, 7th ed., 1967. pp. 16-33.

Thaler, G.J., and R.G. Brown. Analysis and Design of Feedback Control Systems. McGraw-Hill, 2nd ed., New York, 1960.

Truxal, J.G. Automatic Feedback Control System Synthesis. McGraw-Hill, New York, 1955.

CONTENTS

3.4 BASIC CONTROL HARDWARE

Page

3.4.1 Introduction 3.4-1

3.4.2 The Controller 3.4-1

3.4.3 Control Modes 3.4-3

3.4.4 Control Element Characteristics 3.4-4

Bibliography 3.4-11

3.4 BASIC CONTROL HARDWARE

3.4.1 Introduction

In most control loops, two interrelated items of instrumentation combine to regulate the flow rate of a manipulated stream of process material. This section of the Data Book describes the interrelationship of the controller and the control element (control valve) in greater detail than was previously presented, defines some of their specialized features, and emphasizes problems of compatibility that could reduce the performance of a control loop.

3.4.2 The Controller

A process controller is an analog (mechanical) computer that performs a continuous mathematical manipulation based on the error (change) that exists between the controlled variable and the controller set point. Most texts on process control use advanced and specialized mathematics to describe the action of a controller. A working description, however, can be expressed using conventional mathematics.

Generally a feedback control instrument, whether electronic or pneumatic, is based on the principle of the proportional, integral, and derivative (PID) controller. The controller continuously readjusts its output signal using an equation that has this general form:

$$\text{output}_t = k_1 e_t + k_2 \int e\,dt + k_3 \frac{de}{dt}$$

where e_t = error at time "t"

k_1, k_2, k_3 = adjustable controller constants

This equation states the output is the sum of

1. The error existing at the instant multiplied by k_1.
2. An integral term that is the sum of all the errors, both positive and negative, that existed during the time period when the controller was first placed in operation and between time t multiplied by k_2.
3. A derivative term that represents the speed with which the error is increasing or decreasing at a measured instant multiplied by k_3.

In many controllers the value of k_1 is expressed as its reciprocal, the proportional band, PB. The constants k_2 and k_3

are divided by k_1 so that an adjustment of proportional band automatically changes the integral and derivative constants. Thus the controller form is

$$\text{output}_t = \frac{e_t + K_2 \int_0^t e\,dt + K_3 \frac{de}{dt}}{PB}$$

where

$k_1 = 1/PB$
$K_2 = k_2/PB$
$K_3 = k_3/PB$

When a technician adjusts the knobs, levers, or push-buttons on a control instrument to tune the control loop to obtain best operation, he is adjusting the values of the three tuning constants K_2, K_3, and PB. Proportional band is expressed in the units "percent of scale." With a small proportional band (5 to 20 percent), a large change in output occurs with even a small error. With a large proportional band (500 to 800 percent), output changes very little upon detection of an error.

The integral adjustment K_2 sets the relative importance of the integral mode in modifying controller output. Integral is synonymous with reset, which was coined years ago as an advertising term. The integral or reset adjustment is expressed in the unit "repeats per minute," or sometimes by its reciprocal, "minutes per repeat" or an equivalent, "seconds per repeat." The units relate to a standardized test that can be used to measure the value of the constant. With a large "repeats per minute" (0.5 to 20), a continuing error rapidly changes the controller output; this is described as "fast" reset. With a small "repeats per minute" (0.02 to 0.1), the effect of the integral mode in the equation is much reduced, and this is described as "slow" reset.

Derivative adjustment is also expressed in "repeats per minute" or its reciprocal, also relating to an empirical test procedure. In most scrubber applications, the derivative mode will be adjusted between 0.1 and 10 repeats per minute. This mode will usually have less importance than the integral mode in modifying controller output.

3.4.3 Control Modes

Most control loops do not require the use of all three modes; therefore, controllers are built with one or two modes omitted. A one-mode controller contains only proportional control action; constants K_2 and K_3 are set equal to zero. A controller of this type may be required in some feed forward or multiinput control systems where only proportional or ratio action is suitable. One-mode control may also be used in simple control loops where accuracy is unimportant, such as control of liquid level in a tank. In most cases, however, the dampening effect of the integral mode is needed in scrubber feedback loops.

By far the majority of control problems are handled best by a two-mode controller, which contains only proportional and integral modes ($K_3 = 0$). The integral mode causes changes in output to occur more slowly, resulting in fewer surges in the manipulated variable. Of more importance, tuning the integral mode allows the response rate of the controller to match the response rate of the process. With integral mode, control following a disturbance is restored more rapidly and accurately than with proportional control alone.

Only a small percentage of processes require a three-mode controller. While extremely useful in some loops, derivatives cannot be used in others. In contrast to the delaying action of the integral mode, a derivative is designed to overreact to small errors. For example, if the pH of the slurry in a scrubber begins to drop, immediate control action will restore pH more quickly. In this process with a long time lag, the derivative mode responds neither to how far pH has dropped, nor to how long it has been away from set point, but to the rate at which it is dropping. Derivative control would add an extra volume of lime to halt the decrease. When pH stops dropping, the action of the derivative mode would cease. By that time, however, the integral mode, acting more slowly, would be gradually increasing the lime feed rate. Eventually the pH begins to rise, and the derivative mode would act in opposition to the integral mode to prevent overshoot. Properly tuned, derivative control substantially reduces the severity of errors caused by process disturbances. One manufacturer uses the copyrighted name "Pre-Act" to describe its brand of three-mode controllers; the name accurately describes the apparent action. The derivative mode, however, cannot distinguish between a genuine change in the measured variable and a short-term transient change, such as those occurring normally in a flowing stream of material in a pipeline. Derivative control can therefore only be used in loops where a fairly large volume of process fluid is in contact with the sensor, and where the sensor provides a steady signal, free from electronic or process noise. In a lime scrubber, control of pH is a potential application.

Figure 3.4-1 illustrates the response of various controllers in restoring control following a sudden load change or disturbance. While this figure is theoretical, recorded curves of this type are obtained in actual plant loops.

In Table 3.4-1, recommended control modes are shown for the type of controls found in lime scrubbing systems.

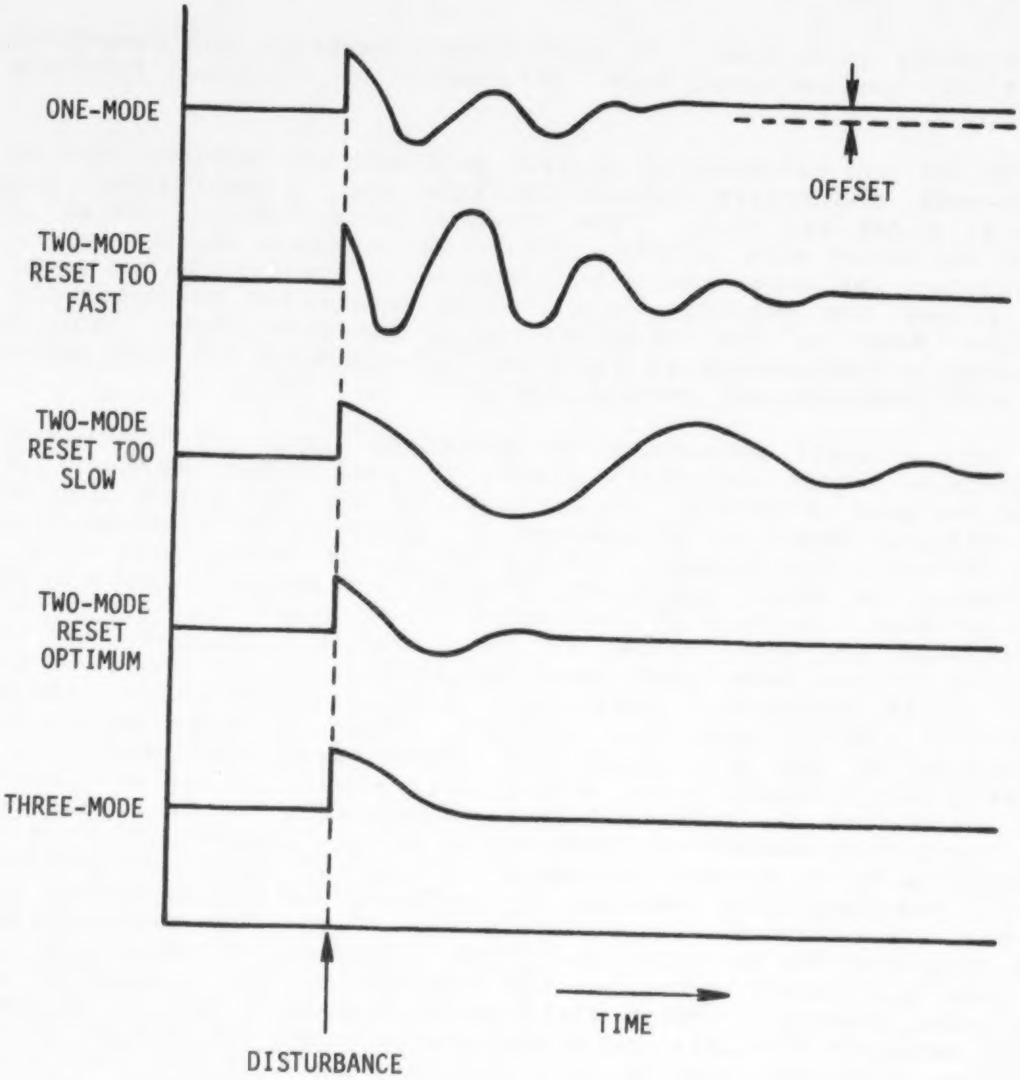

ONE-MODE
OFFSET
TWO-MODE RESET TOO FAST
TWO-MODE RESET TOO SLOW
TWO-MODE RESET OPTIMUM
THREE-MODE
TIME
DISTURBANCE

Figure 3.4-1. Theoretical controller response curves.

Table 3.4-1. RECOMMENDED CONTROL MODES

	Proportional	Integral	Derivative
pH	x	x	x
Level	x		
Solids	x	x	
Gas volume	x	(x)[a]	
Reheat	x	x	

[a] Not required if proportional control is based on actual pressure vs. flow rate measurements.

3.4.4 Control Element Characteristics

A detail of control system design closely related to the action of a controller is the response characteristic of a control valve or other control element. The proportional band of a controller is always adjusted to change the controller output by a definite amount in order to correct an error of a certain magnitude. This ratio is dictated by the response of the process to a certain change in the manipulated variable. It follows, therefore, that for ease of design the manipulated variable should change in direct linear ratio with the controller output. In other words, an incremental change in controller output should produce an incremental change in the manipulated variable, regardless of the initial value of the manipulated variable. If this is not the case and if the controller is tuned when the process is operating at full load, the controller will apparently be out of tune when the process is dropped to half load. In many operating control loops, the controller can be tuned to operate well only over a narrow range of operating flows. Above or below this range, the proportional band of the controller must be readjusted for the loop to operate properly. The fault is not with the controller but with the operating characteristic of the control element. It should be remembered that if one element of a control loop is nonlinear, the loop is nonlinear (for example, pH sensors behave nonlinearly).

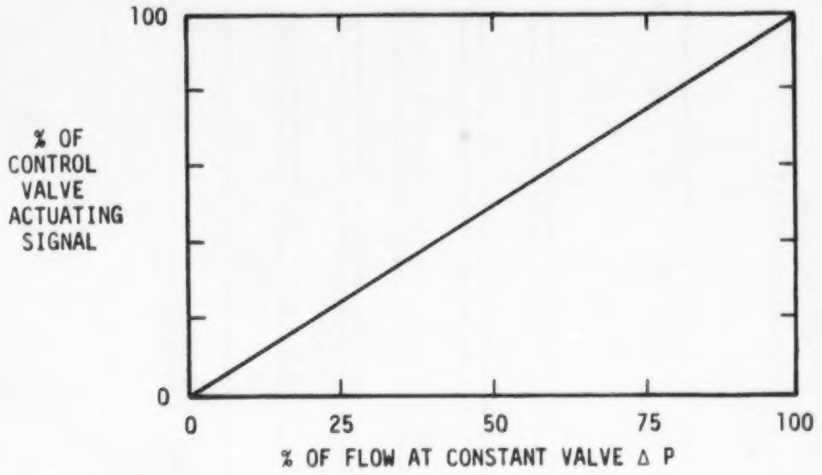
Linear loops are not inherently better than nonlinear loops, although they are much easier to design. Stability is easier to maintain in linear systems. Some variables can be easily transformed to linear forms. Thus, sensing pressure drop, ΔP, in an orifice plate requires only a square root function to produce flow rate. A digital controller accomplishes this with ease.

Some control valves are manufactured with a linear control characteristic. At a constant pressure drop, valves of this type produce a flow rate that is directly proportional to the value of the actuating signal (Figure 3.4-2a). A control loop that includes a valve of this type will provide accurate control under any loading conditions, providing all other conditions retain a linear relationship and pressure drop through the control valve remains constant.

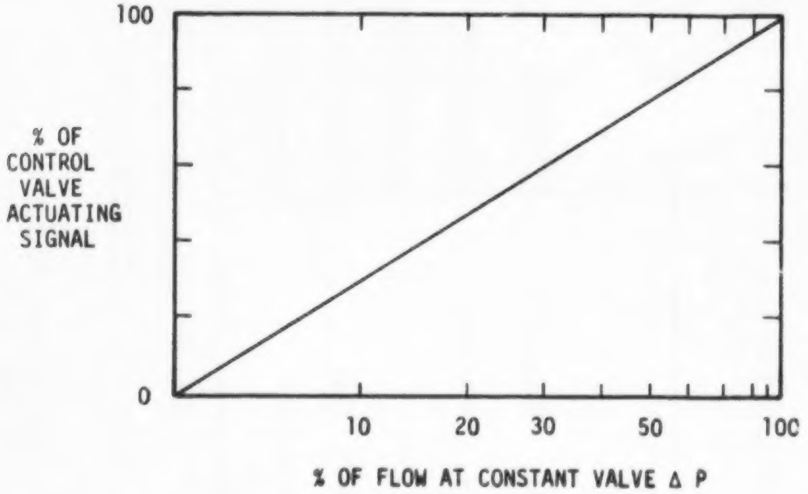
In most instances, however, other conditions do not remain constant; valve friction increases and pump discharge pressure decreases as the flow rate increases. Therefore, pressure drop across the control valve may decrease significantly as flow rate increases. A valve with a linear characteristic does not produce a flow rate proportional to controller output if valve pressure drop varies as flow rate changes.

In a practical development some years ago, control valves were designed so the controller output signal would be proportional to the logarithm of the flow rate passing through the valve at constant pressure drop (Figure 3.4-2b). Valves of this type are said to have an equal percentage control characteristic. They were designed to match more closely the pattern of pressure and flow created by conventional chemical engineering design practices, using a centrifugal pump to deliver the manipulated stream. In some loops, for instance, the equal percentage valve characteristic is a very close match to operating conditions, and a wide range of operating rates can be accommodated without necessitating retuning of the controller.

In many control loops, however, neither a linear nor an equal percentage valve characteristic is sufficient. To obtain best control, these loops ought to be supplied with individually designed valves. However, valves with special characteristics are not manufactured, since there are other ways to control the system. In loops where the manipulated variable is always expected to operate within a narrow range of flow rates, it is advisable to accept the mismatch and choose between the two commercially-available characteristics. In general, if the configuration of the loop is such that little change in pressure drop will occur with a change in flow, the linear characteristic is better. In loops with long piping runs, where pressure drop due to friction is significant, the equal percentage characteristic is better. A rule of thumb for various types of conventional control loops is shown in Figure 3.4-3. Since flow of heat is not proportional to flow of heating medium, equal percentage valves are better for almost all temperature control loops. In fact, in no loop is flow of the manipulated variable in exact linear ratio to its effect on the controlled variable, except in direct flow rate control loops.

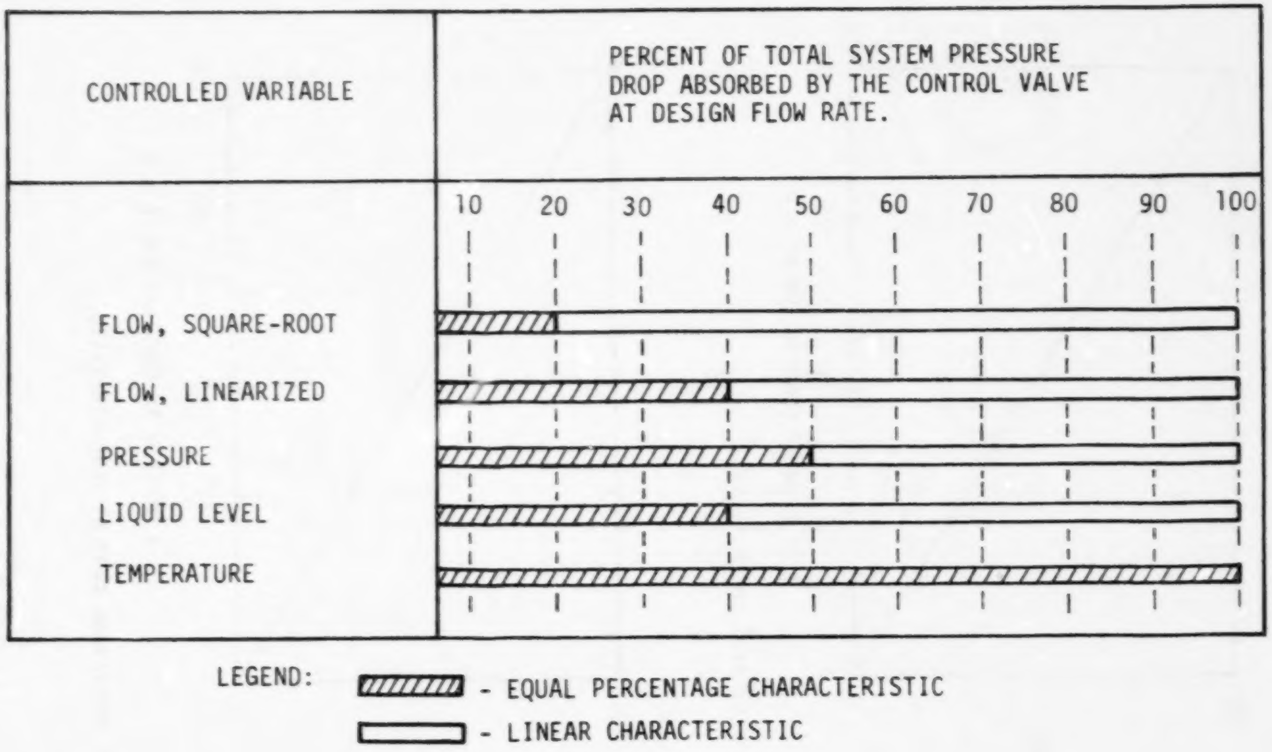


a. Linear control characteristic.



b. Equal percentage control characteristic.

Figure 3.4-2. Valve characteristics.



REFERENCE: PUBLICATION, FOXBORO COMPANY, 1974

Figure 3.4-3. Selection of control valve characteristics.

Source: Foxboro Co., 1974.

If the loop control must operate properly over a wide range of flow rates, several alternatives can be used. If a digital computer is being used, rather than a conventional analog instrument, the proportional band is simply readjusted as controller output changes. This is one of the advantages of digital process control.

With analog control, correction is possible through the use of cascade control. As described previously, in cascade control a flow loop is added to the manipulated variable, and the output of the primary controller manipulates the set point of the secondary flow controller. If the flow rate sensor produces a signal that is linear with flow, the primary controller "sees" a linear characteristic. Good control is achieved over a wide range. Cascade control does not eliminate the mismatch; it merely transfers it to the flow control loop. However, control of flow rate can be less than optimal without causing an error in the much-slower primary loop.

An alternative method is to add a cam-type valve positioner to the control valve. This device is interposed between the controller and the control valve actuator. An internal cam is cut to a slope that modifies the signal in a manner that achieves, for a specific loop, the desired linear flow rate. While less expensive in initial cost, this method requires the services of an experienced field technician to determine and produce the proper cam configuration. This method was widely used at one time but is now rarely employed because of the wider use of digital control.

The greatest problems with mismatch in valve characteristic will occur when valves with an inherently nonlinear characteristic are used. Valves such as butterfly, ball, knife, gate, and pinch are desirable in other respects, but they perform very poorly when used without supplemental devices in control applications. To obtain wide range control with these valves, it is essential that cam-type valve positioners be used. The application of positioners to these valves does not necessitate extensive field work, since vendors can usually supply precut cams that convert the valves to the equivalent of linear or equal percentage control characteristics. However, none of these valves should be used as control valves in erosive slurry systems.

If variable-speed pumps are used instead of valves, as the control element, the same characteristic principles apply. Variable-speed centrifugal pumps may have an extremely nonlinear response and may require special mechanical or electronic accessory devices to achieve adequate control. On the other hand, positive displacement pumps with variable drive motors most often have very good control characteristics.

BIBLIOGRAPHY

Chestnut, H. Systems Engineering Tools. Wiley, New York, 1965; p. 613.

Clark, R.N. Introduction to Automatic Control Systems. Wiley, New York, 1962.

Doeblin, E.O. Dynamic Analysis and Feedback Control. McGraw-Hill, New York, 1962.

Dorf, R.C. Modern Control Systems. Addison-Wesley Publishing Co., Reading, Massachusetts, 1966.

Electro-Craft Corporation. Motomatic Speed Control. Hopkins, Minnesota, 1964.

Horowitz, I.M. Fundamental Theory of Automatic Linear Feedback Control System. IRE Trans. on Automatic Control, Dec. 1959.

Kuo, B.C. Automatic Control Systems. Prentice-Hall, Englewood Cliffs, New Jersey, 1962.

Lime/Limestone Scrubber Operation and Control Study. Report prepared by Southern California Edison Co., EPRI (RP630-2), April 1978.

Marks, L.S. Standard Handbook for Mechanical Engineering. McGraw-Hill, 7th ed., 1967. pp. 16-33.

Schultz, W.C., and V.C. Rideout. Control Systems Performance Measures: Past, Present, and Future. IRE Trans. on Automatic Control, February 1961.

REFERENCES

1. Foxboro Company. 1974.

SECTION 4

EQUIPMENT DESIGN

4.1 INTRODUCTION

This section includes design information, to supplement that with which a design engineer should be familiar and to assist in determining the type of equipment needed for a particular FGD system. The following topics are discussed:

Section	Equipment
4.2	Recirculating Pumps
4.3	Other Process Pumps
4.4	Lime Unloading and Storage
4.5	Slurry Preparation
4.6	Scrubber/Absorber
4.7	Mist Eliminator
4.8	Fans
4.9	Thickener/Clarifier
4.10	Mechanical Dewatering Equipment
4.11	Reheaters
4.12	Corrosion
4.13	Instrumentation

The characteristics of the equipment, design considerations and criteria, materials of construction, and a review of the equipment used at various lime FGD system installations are presented. Specific areas of concern such as the causes of equipment failure (insofar as they are known) are reviewed for operational installations.

The emphasis of this section is on data that must be considered in order to design the best operational lime FGD system for an individual site.

CONTENTS

4.2 RECIRCULATION PUMPS

Page

4.2.1 Introduction 4.2-1

4.2.2 Design Criteria 4.2-5

  4.2.2.1 Service Description 4.2-5
  4.2.2.2 Flow/Head 4.2-7
  4.2.2.3 Net Positive Suction Head 4.2-7
  4.2.2.4 Pump Efficiency and Energy Requirements 4.2-8
  4.2.2.5 Impellers 4.2-8
  4.2.2.6 Drives 4.2-10
  4.2.2.7 Seals 4.2-10
  4.2.2.8 Materials of Construction 4.2-12
  4.2.2.9 Vendor Specifications 4.2-13
  4.2.2.10 Auxiliary Design Considerations 4.2-15

4.2.3 Performance Histories 4.2-15

References 4.2-20

4.2 RECIRCULATION PUMPS[1,2]

4.2.1 Introduction

The purpose of this section is to supplement the design engineer's basic knowledge by an analysis of recirculation pump design. Emphasis is placed on features that are unique to the design of slurry recirculation pumps used in lime FGD systems.

The recirculation pumps are the largest pumps in a lime FGD system (Figure 4.2-1), with capacities ranging from 5000 to 15,000 gal/min. They receive the slurry directly from the bottom of the scrubber or from a reaction/hold tank. The discharge slurry is continuously recirculated through the absorber. Normally, a portion of the recirculation stream is bled to the solids disposal system. Occasionally, the pumps may have variable speed drive to allow liquid flow control, but as a rule the pumps operate at constant speed and supply constant liquid flow, even though the flue gas flow may be variable.

A typical slurry pump has many features (Figure 4.2-2) that set it apart from the typical centrifugal pump used for clear liquids. Wall thicknesses of wetted-end parts (casing, impeller, etc.) are greater than in conventional centrifugal pumps. The cutwater, or volute tongue (the point on the casing at which the discharge nozzle diverges from the casing), is less pronounced in order to minimize the effects of abrasion. Flow passages through both the casing and impeller are large enough to permit solids to pass without clogging the pump. Since the gap between the impeller face and suction liner will increase as wear occurs, the rotating assembly of the slurry pump must be capable of axial adjustments to maintain the manufacturer's recommended clearance. This is critical if design heads, capacities, and efficiencies are to be maintained. Other specialized features include extra-large stuffing boxes, replaceable shaft sleeves, and impeller back-vanes that act to keep solids away from the stuffing box. Although the impeller back-vanes also reduce axial thrusts by lowering stuffing-box pressures, these vanes can wear considerably in abrasive services. Hence, both the radial and the axial-thrust bearings on the slurry pump are heavier than those on standard centrifugal pumps.[3]

Because recirculation pumps handle abrasive slurry, their design involves special considerations, many of them related to the selection of materials. Recirculation pumps are available in a variety of materials of construction to handle the abrasion, corrosion, and impact requirements of the solids-handling application.

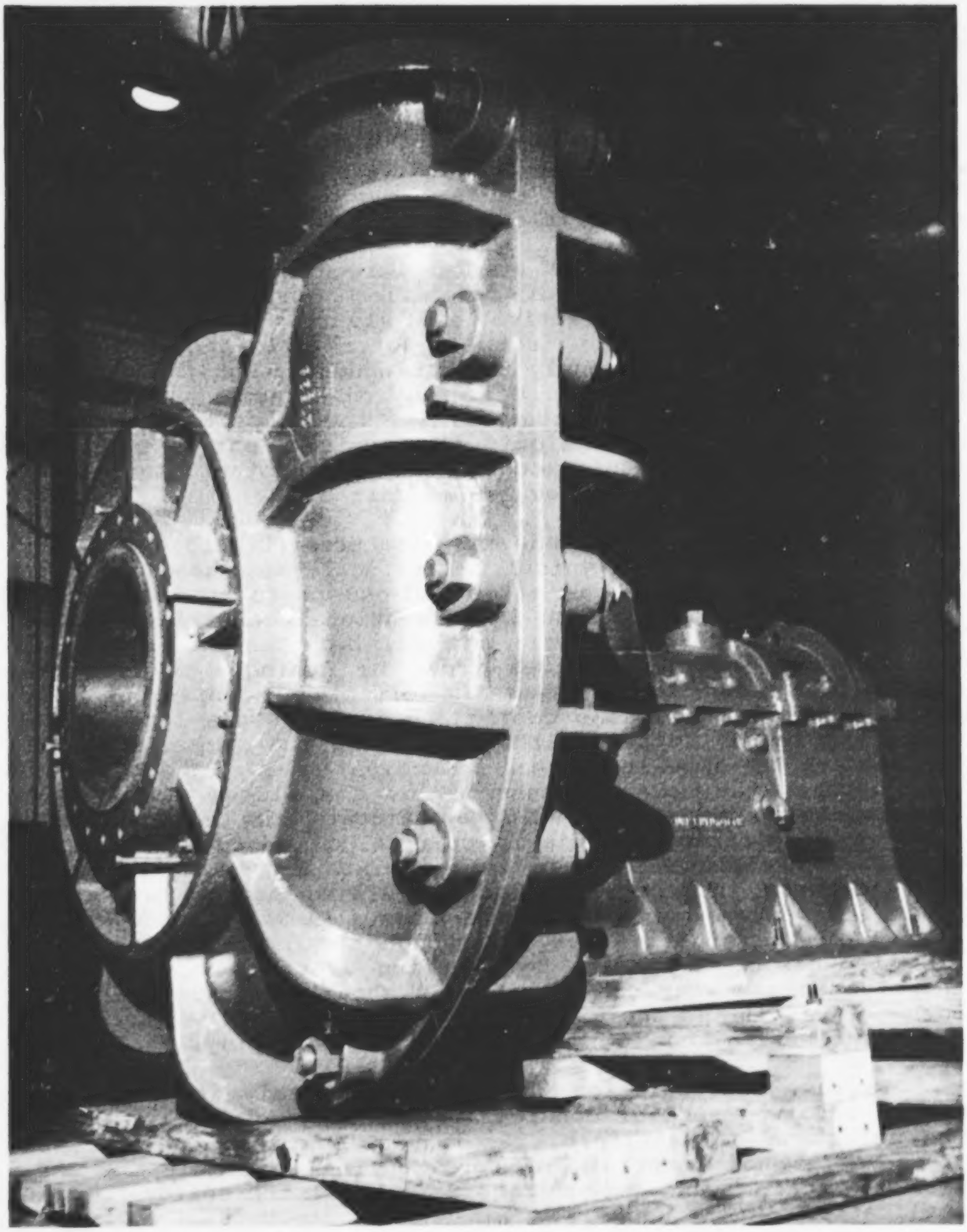


Figure 4.2-1. Scrubber slurry recirculation pump.

Source: A-S-H Corporation

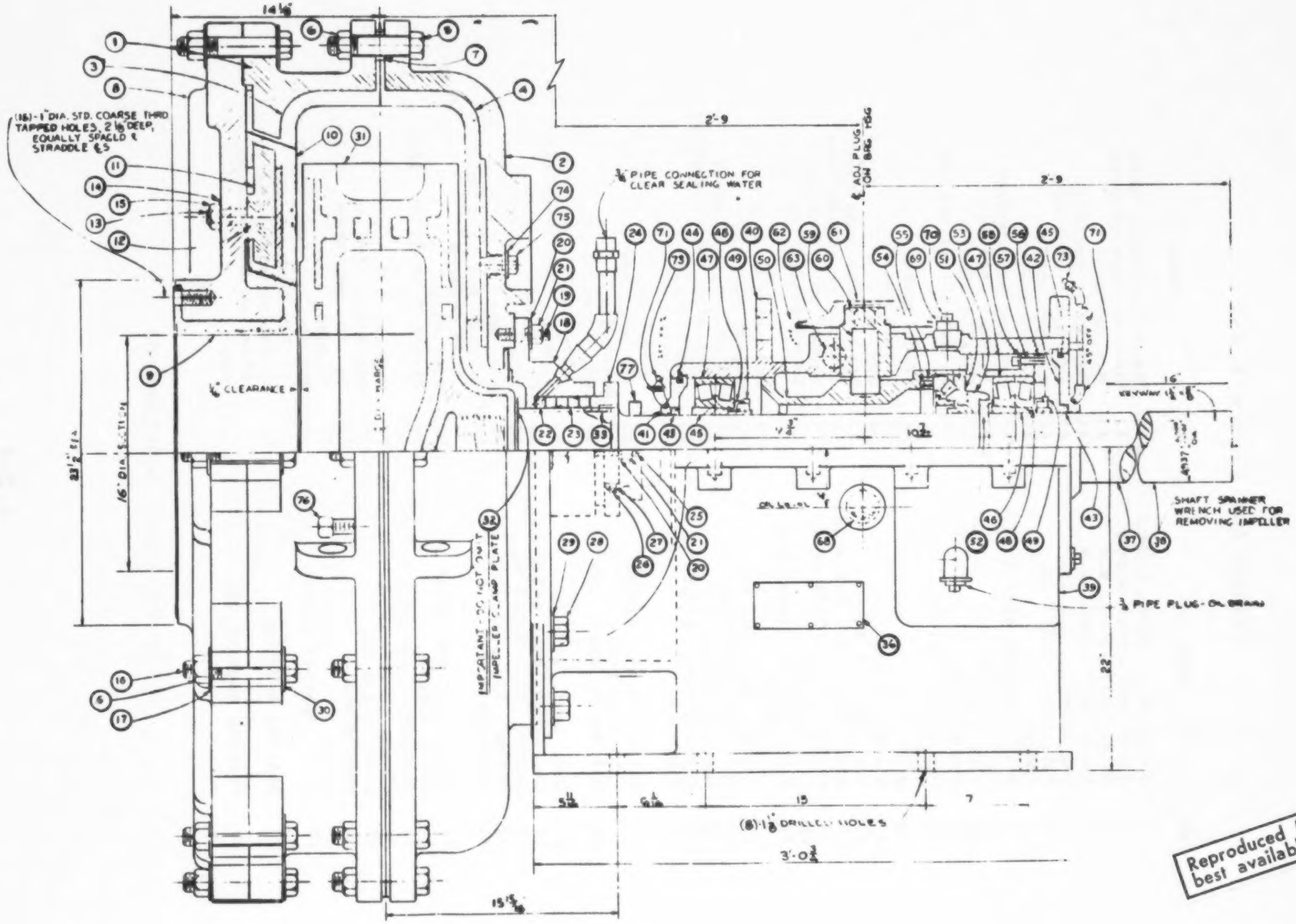

(16)-1" DIA. STD. COARSE THRD TAPPED HOLES, 2 1/16 DEEP, EQUALLY SPACED & STRADDLE ℄S
14 1/8"
2'-9
3/4" PIPE CONNECTION FOR CLEAR SEALING WATER
℄ ADJ PLUG ON BRG HSG
1/4" CLEARANCE
IMPORTANT - DO NOT OMIT IMPELLER CLAMP PLATE
16" DIA
23 1/2" DIA
SHAFT SPANNER WRENCH USED FOR REMOVING IMPELLER
3/4 PIPE PLUG-OIL DRAIN
(8)-1 1/8 DRILLED HOLES
3'-0 3/4
15 15/16"
22"
16"
15
7

Figure 4.2-2. Slurry recirculation pump detail assembly (A-S-H, DG95-pump).

(continued)

Reproduced from best available copy.

Legend for Figure 4.2-2

No.	Name
1	Shell half, suct. side (S.S.)
2	Shell half, eng. side (C.S.)
3	Shell half liner, s.s.
4	Shell half liner, e.s.
5	Cap screw, 1-1/4 in.
6	Nut, hex., 1-1/4 in.
7	Spacer
8	Bell, suction side (S.S.)
9	Throat liner
10	Side liner
11	Spacer ring
12	Car screw, fl. hd. 3/4 in.
13	Stud, 1 in.
14	Washer, 1 in.
15	Nut, hex., 1 in.
16	Bolt, hex. hd., 1-1/4 in.
17	Washer, fl., 1-1/4 in.
18	Stuffing box
19	Stud, 3/4 in. (stuffing box/shell)
20	Washer, fl., 3/4 in.
21	Nut, hex., 3/4 in.
22	Lantern ring
23	Packing ring, gland
24	Gland half
25	Stud, 3/4 in. (gland/stuffing box)
26	Cap screw. hex., 1/2 in.
27	Nut, hex., 1/2 in.
28	Cap screw, hex, 1-1/4 in.
29	Washer, fl., 1-1/8 in.
30	Washer, fl., 1-1/4 in.
31	Impeller
32	Impeller clamp plate
33	Shaft sleeve
34	Jackscrew, sq. hd., 1 in.
35	Stud, 1-1/4 in.
36	Name plate
37	Shaft
38	Shaft spanner wrench
39	Bearing housing
40	Bearing housing cap
41	Bearing housing cover
42	Bearing housing cover
43	Garlock seal
44	Hydraulic packing
45	Hydraulic packing
46	Adaptor sleeve
47	Roller bearing
48	Bearing lock washer
49	Bearing lock nut
50	Bearing spacer
51	Roller thrust bearing
52	Split spacer
53	Thrust collar
54	Spring
55	Spring retaining ring
56	Bearing retaining ring
57	Socket hd. cap screw
58	Lock washer, 1/2 in.
59	Adjusting plug pin
60	Adjusting plug
61	Adjusting plug cover
62	Retaining chain assembly
63	Locking pin
64	Locking pin nut, 1-5/8 in.
65	Jam nut, hex., 1-5/8 in.
66	Cap screw, 1 in. (cap/hsg.)
67	Washer. lock 1-in. std.
68	Oil gauge
69	Pipe plug, 1-1/2 in.
70	Air vent
71	Service ell, 1/8 in. x 45 degrees
72	Pipe clip
73	Grease fitting No. 1610
74	Washer, 5/8 in.
75	Cap screw, 5/8 in.
76	Sq. hd. jackscrew, 1 in.
77	Flinger
78	Warning tag (not shown on BRG housing cap)
79	Direction arrow (not shown on BRG housing cap)

Figure 4.2-2 (continued)

4.2.2 Design Criteria

4.2.2.1 Service Description--

In order to select recirculation pumps properly, a comprehensive service description must be developed. This necessitates detailed analysis of the parameters described below:

Composition--The fluid to be pumped is a slurry containing many solid and dissolved species. The major solids are lime, fly ash, calcium sulfite ($CaSO_3 \cdot 1/2H_2O$), and calcium sulfate ($CaSO_4 \cdot 2\ H_2O$), all of which are erosive. Solids levels normally range from 5 to 20 percent by weight. The dissolved species include calcium, magnesium, sodium, sulfite, sulfate, chloride, and carbonate ions, together with the ion pairs, such as hydrogen and hydroxide ions. Before specifying materials of construction for a recirculation pump system, the designer must know the chemical analysis of the specific slurry. This is particularly important with closed-loop operation, since species present only in trace amounts, such as chloride ions, can build up to critical levels of 1000 ppm or more and dictate the use of highly corrosion-resistant materials. In addition, the nature, concentration, and size distribution of the solids should be known. Information about all these important elements is necessary to determine abrasion-corrosion resistance and the mechanical strength required of the pump.

pH--The slurry pH at the inlet to the absorber is usually controlled to between 7 and 9, whereas the pH at the absorber outlet ranges from 5 to 6. The recirculation pump is normally located after the reaction tank. Therefore, it will be exposed to a pH of about 7 or more. On systems without a reaction tank, such as Bruce Mansfield, or where there is a pump both before and after the reaction tank, such as Paddy's Run, the pH at the recirculation pump inlet will be lower. Thus, the pump location determines the pH to which the pump material will be exposed. The pH values are an important factor in the selection of pump materials.

Specific Gravity--The specific gravity of the recirculating slurry is usually between 1.05 and 1.14. Figure 4.2-3 is a graphic representation of specific gravity as a function of the solids content of the slurry. In systems that incorporate automatic solids control, the specific gravity of the slurry is relatively constant. Many systems, however, do not control solids content, and the specific gravity varies over a wide range.

Viscosity--Knowing details of the rheology of the slurry makes it possible to evaluate the reduction in pump performance due to the viscosity of the mixture and the added slip between the fluid and the solid particles as the mixture accelerates through the pump impeller. This slip is greater in mixtures with higher settling velocities.

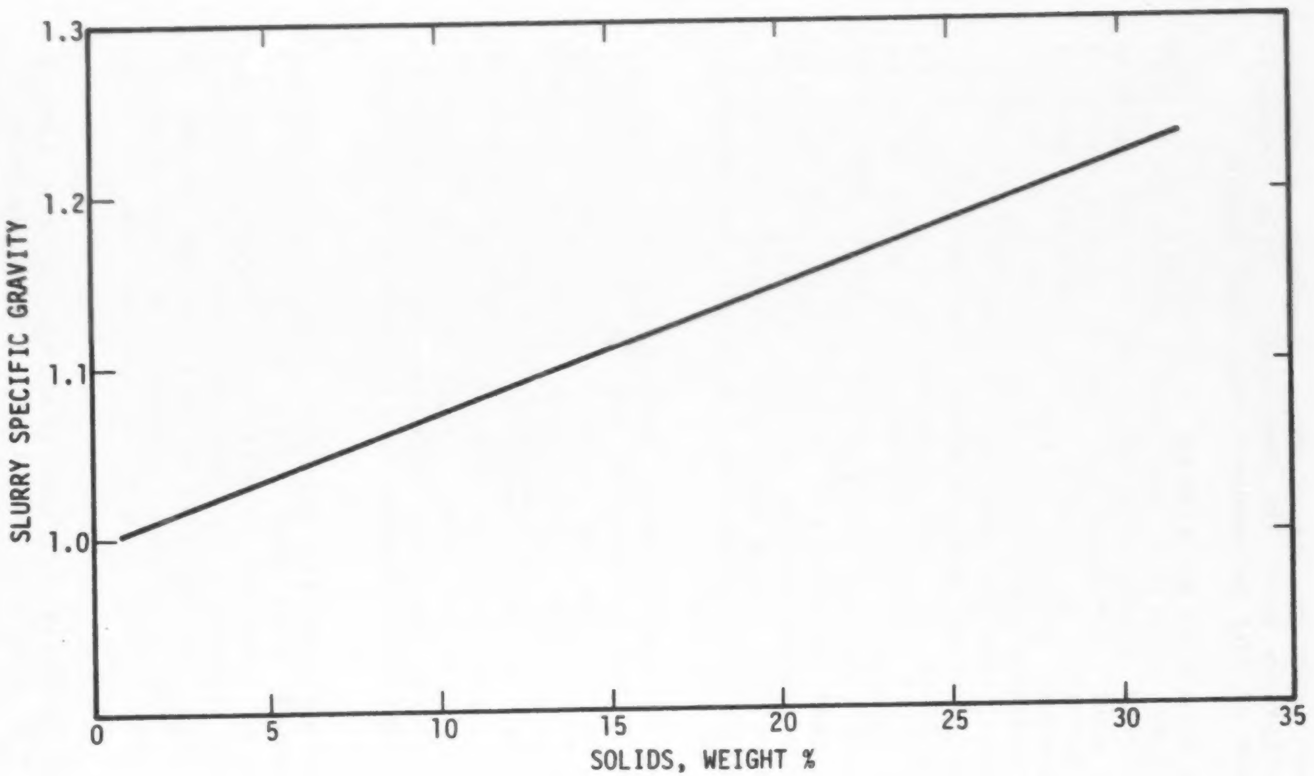


Figure 4.2-3. Specific gravity of scrubber recirculation slurry.

Ash--The slurry may contain significant amounts of fly ash, depending on the coal and the amount of flue gas pretreatment. The amount and type of ash must be determined prior to equipment specification, because certain types of ash increase the erosive action of a slurry.

Gas Entrainment--It is possible that the recirculating slurry could contain entrained flue gas as it exits from the scrubber. Gas entrainment can result in the slurry in the pump ranging from all liquid to essentially all gas. These variable conditions, if allowed to exist, can cause shaft deflection, which may result in bearing failure and abnormal packing wear. Gas entrainment also reduces the liquid flow, which can reduce SO_2 absorption. Adequate phase separation in the scrubber will prevent this problem.

4.2.2.2 Flow/Head--

Low-speed operation is one of the most important wear-reducing features of a slurry pump. Pump abrasive wear increases proportionally to the third power of rpm. Impeller tip speed of rubber-lined pumps is limited to 3500 to 4500 ft/min. This limits the rpm of the recirculation pumps with rubber linings to 400 to 600 rpm, which corresponds to a maximum discharge head of about 100 ft.

Total liquid flow rate required for the absorber is determined by the design L/G ratio. The normal recirculation flow rate range, corresponding to the rpm and head limitations, is 6000 to 10,000 gal/min for a rubber-lined pump. The number of pumps required per scrubber, other than spares, is determined by a technical and economic analysis of alternatives over the specified range.

4.2.2.3 Net Positive Suction Head (NPSH)--

It is necessary to differentiate between available NPSH, absolute suction head, and required NPSH. The available NPSH, which is a characteristic of the system in which a centrifugal pump works, represents the difference between the existing absolute suction head and the vapor pressure of the slurry at the operating temperature. The absolute suction head is the algebraic sum of the suction pressure, static head, and the frictional loss in suction line at a given capacity. With a given static pressure at the suction side and a specific slurry temperature, the available NPSH is reduced with increasing capacities by the friction losses in the suction piping. The design engineer must specify the available NPSH to the pump manufacturers.

In a pump, the pressure at any point in the suction line must never be reduced to the vapor pressure of the liquid because of the danger of cavitation. The required NPSH, which is a function of the pump design, represents the minimum required margin between the suction head and vapor pressure at a given capacity. The factors determining required NPSH include suction area of the impeller, shape and number of impeller vanes, impeller velocity, and the impeller eye area (the annulus between hub and vane walls). The required NPSH, which increases basically as the square of the capacity, must be obtained from the pump manufacturer. Most slurry pumps require an NPSH of 15 to 30 ft.

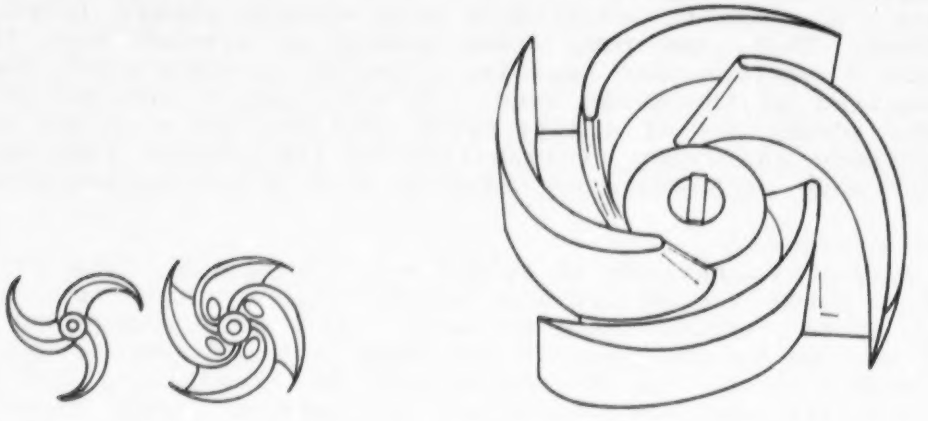
The available NPSH must be determined accurately. More pump troubles result from incorrect determination of available NPSH than from any other single cause. As the available NPSH for a given pump decreases, its capacity and efficiency decrease, and a low-suction pressure develops at the pump inlet. The pressure decreases until a vacuum is created and the liquid flashes to vapor (if the pressure is lower than the liquid vapor pressure). This condition, which can lead to cavitation damage, must be avoided by ensuring that the available NPSH is greater than the required NPSH.

4.2.2.4 Pump Efficiency and Energy Requirements--[4,5]

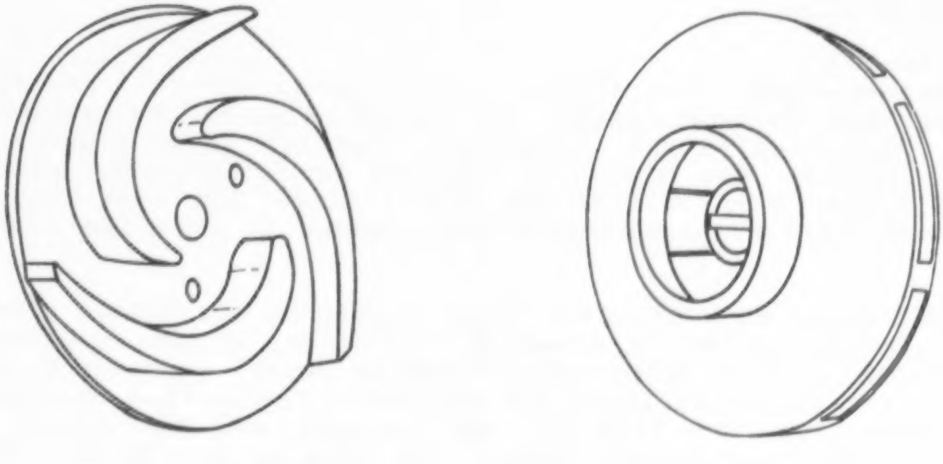
The selection of efficiency should not be left entirely to the pump manufacturer. He should be given data regarding energy costs, the service conditions, and flow and head requirements. An energy cost of 3¢/kWh and a penalty of $1000 per additional horsepower can be specified as the basis for preliminary comparisons with the most efficient pump. Variations in size and efficiency result from each manufacturer's effort to choose, from his standard line of pumps, the one that most closely meets the required conditions. Hence, the specifications should not be so restrictive as to cause exclusion of high-efficiency pumps. Finally, when the efficiency penalty is less than 10 percent, the pump with lower speed should be selected because the increased pump life will compensate for the slightly higher operating costs.

4.2.2.5 Impellers--

The impeller consists of a number of vanes open, semiopen, or shrouded. The shrouded (closed-type) impeller has shrouds on both sides to enclose the liquid passages. The closed- or semiopen-type impeller is generally more efficient and is used for service with abrasive slurry (See Figure 4.2.4). Closed impellers experience less loss in efficiency than do open impellers with the same widening of face clearance between the impeller and the casing wall. An accelerated wear test of open and closed impellers of otherwise identical geometry showed that when the clearance of both impellers opened to 0.050 in., the efficiency of the open impeller dropped by 28 percent, whereas that of the closed impeller fell only by 14 percent.[6] It has



(a) OPEN IMPELLERS: IMPELLERS ON THE RIGHT ARE STRENGTHENED BY PARTIAL SHROUDS.



(b) SEMIOPEN IMPELLER

(c) CLOSED IMPELLER

Figure 4.2-4. Types of impellers for recirculation pumps.

already been pointed out that low-rpm operation is of the utmost importance in reducing wear. For highly abrasive applications, therefore, a range of acceptable pump speeds should first be determined. Then, the pump speed should be altered over this range and a maximum-size impeller selected to obtain the capacity required at the given head. In addition to reduced parts wear, the advantages of a full-sized impeller are a slight gain in efficiency and ready availability of replacement impellers, which are made of Ni-Hard or chromium iron or are rubber-lined.

4.2.2.6 Drives--

Slurry pumps operate at relatively low speeds, from 400 to 600 rpm. Since the motors are either 1800 or 1200 rpm, some type of speed reducer must be used. The most common way of driving a lime slurry pump is by using a V-belt drive with a fixed ratio, which has the advantages of flexibility and low cost. For applications above 300 hp, however, gear reducers should be considered. V-belt drives can be overhead-mounted or side-mounted on horizontal pumps. Since it is difficult to determine friction values of certain slurries for which data are not readily available, it is advisable to use V-belt drives with variable-pitch diameters. Without increasing the initial purchase cost to a great extent, these drives simplify balancing of the system at startup, allow the pump to meet future changes in flow rate and head, reduce deterioration of pump performance due to wear, and allow correction to initial system design for a particular slurry.

4.2.2.7 Seals--

Horizontal-type centrifugal slurry pumps have a shaft passing through the pump casing, which must be sealed to prevent leakage. Mechanical seals, which are used for clean liquids, are not suitable for slurries. Packed stuffing boxes have customarily been used to seal the shafts since they cost less, allow faster repair, and usually last longer in abrasive service.

A continuous flow of clear water should be introduced into a lantern ring at an intermediate position in the packing (Figure 4.2-5). This flush water prevents abrasive solids from entering the critical stuffing box and shaft sleeve area thereby greatly extending the life of the packing and the sleeve. Because abrasive solids may enter the packing during an FGD system shutdown or upset, the pump should be designed with a shaft sleeve of hardened alloy. Even under the best operations, abrasive slurry may enter the packing.

The flush water entering the stuffing box will flow either past the packing into the process or out the stuffing box. The volume of flush water that mixes with the recirculating slurry

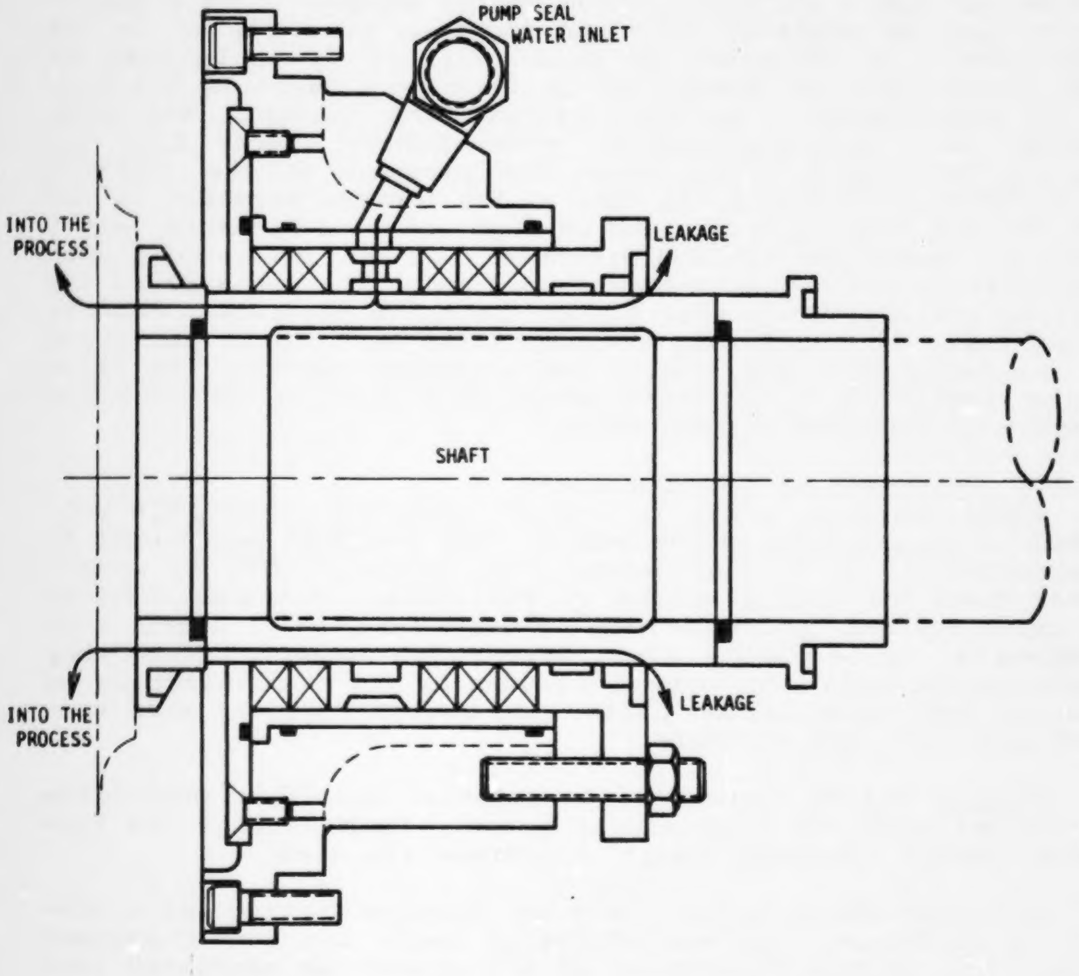

PUMP SEAL WATER INLET
INTO THE PROCESS
LEAKAGE
SHAFT
INTO THE PROCESS
LEAKAGE

Figure 4.2-5. Pump seal water flow.

may be sufficient to affect the scrubber system water balance (Section 2.2.3.3, Sample Calculations). As a housekeeping measure, a large-diameter drain line should be provided to carry the leakage from the stuffing box to the sump. For closed-loop systems, the sump water should be pumped to the thickener.

The flush water supply system must be external to the scrubber system and reliable enough to deliver a minimum quantity and pressure at all times. Process water can be considered for use if the suspended particulate matter is less than 40 μm in size and has a maximum of 1000 ppm by weight.[7] The required clarity may be achieved with the addition of a filter in the water line. If thickener or pond overflow is to be used as flush water, use of flocculant is necessary (Section 4.9.3.2, Use of Flocculant). In most slurry pump designs, the pump impeller will have back-vanes, which remove slurry from the stuffing box region. This makes the pressure in the stuffing box assembly essentially the same as the suction pressure to the pump, so the sealing fluid need be supplied at a pressure only 5 to 10 psi above the suction pressure. On designs without such back-vanes or with an excessively worn pump, the pressure in the stuffing box region may rise to the discharge pressure. Then it is necessary to supply the sealing fluid at 5 to 10 psi above the discharge pressure. As a precautionary measure, an alarm may be installed on the seal water feed line to indicate low pressure or low flow of seal water.

4.2.2.8 Materials of Construction--

Since the pump parts in contact with the slurry are subjected to abrasive-corrosive action, the "wetted" parts must be constructed of a corrosion-resistant material that is either harder than the slurry solids or resilient. The pump casings and impellers are typically made of hardened iron or steel, such as Ni-Hard, or of carbon steel lined with rubber. Since pump manufacturers will not accept responsibility for selection of material for these wetted parts, the design engineer must know which materials are suitable.

Rubber--Molded rubber is the material specified most often for wetted parts of lime slurry pumps. Both natural and synthetic rubbers of about 1/4-in. thickness are used.

Although rubber is resilient in abrasive service and resistant to corrosion, the use of rubber parts has some disadvantages. One is the limitation of tip speed, as mentioned earlier, and the resultant limitation of head to about 100 ft. In addition, the entry of tramp metal (welding rods, bolts) into the pump can destroy the rubber impeller and lining. At one facility, strainers were installed in the pump section to protect the lining. When the strainers plugged, however, the pump cavitated, stripping the lining from the casing. The strainers have been removed from the recirculation piping. Once the impeller or lining rubber is damaged, it cannot be repaired and must be replaced with new factory-supplied parts. Hence if strainers are to be used, they should be accompanied by efficient cleaning devices.

Hard Iron--Ni-Hard is a cast iron containing nickel (4%) and chrome (1.4 to 3.5%). It is a very hard, brittle material (550 to 650 Brinell) that can be finished only by grinding. Ni-Hard has been used successfully in scrubber applications where good pH control is achieved. It should not be subjected to pH below 4. Ni-Hard is superior to rubber in that it allows higher heads and is not as vulnerable to damage by tramp metal.

Alloys--Alloy-20, which contains nickel (35%); chromium (20%); copper (3.5%); and molybdenum (2.5%), was applied unsuccessfully on a lime slurry pump at one installation. Although this alloy offers good corrosion resistance under many applications, the eroding action of the slurry removed the passivating film and allowed corrosion to proceed at a high rate. The lining and impeller failed in 3 months. For details on other materials tested at this site, see Section 4.2.3, Performance Histories--Phillips.[8,9,10]

Ceramics--Ceramic lining is being used more frequently in vessels and piping. Although some manufacturers produce ceramic pump liners, not one is currently in service on scrubber slurry pumps. Ceramics provide excellent resistance to corrosion and abrasion, but they are brittle and subject to shock failure.

4.2.2.9 Vendor Specifications--

As part of the Data Book project, several pump vendors were asked to bid on a typical recirculation pump. Table 4.2-1 shows results of this survey, in which each vendor was requested to specify a pump for operation under the following lime scrubber conditions:

Flow: 9000 gal/min max., 8200 gal/min normal
Head: 100 ft max.
Service: Lime slurry, $CaSO_3 \cdot 1/2H_2O$, $CaSO_4 \cdot 2H_2O$, fly ash
Slurry specific gravity: 1.05 to 1.14
Temperature: 120° to 135°F
Solids: 5 to 10 percent
Size of solids: -100 mesh
Available NPSH: 30 ft

It is noted that pump efficiencies vary from 71 to 84 percent, whereas pump speeds vary from 470 to 800 rpm. Assuming a minimum required efficiency of 75 percent and a maximum allowable speed of 500 rpm, preliminary comparison would lead to the first two vendors. For further details on evaluation procedures, see Bid Evaluation Section 5.5.

Table 4.2-1. SURVEY OF VENDOR PUMP SPECIFICATIONS
(Flow 9000; Net Head, 100)

Characteristics	Allis Chalmers	Allan Sherman Hoff	Worthington	Ingersoll Rand	Nagle	Denver Equipment Co.
Pump characteristics						
Pump	SRL-C	D-G- 9-5	12 R 265	400 CIR	16 KR	NR
Pump dimensions, in.	16 x 14 x 34	16 x 16 x 39	14 x 12 x 36	16 x 12 x 27.94	15 x 33	16 x 14 x 28
Impeller eye area, in.^{2}	189	201	148.5	154	NR	182.65
Efficiency, %	85	76	77	72	76	71
Pump speed, rpm	510	470	800	720	NR	670
BHP @ design	305	300	300	NR	NR	365
BHP max.	350	342	340	368	339	392
Construction						
Lining	Nat. rubber	Hypalon rubber	Nat. rubber	Nat. rubber	Nat. rubber	Nat. rubber
Casing	Cast iron	Cast iron	Cast iron	Carbon steel	Cast iron	Cast iron
Impeller	Rubber	Rubber	Steel	Steel	Cast iron	Cast iron
Shaft	SS	316 SS	SS	SS	Hastelloy 18	Alloy steel
Wear rings	No	NR	NR	NR	NR	SS
Drive	Belt	Belt	Belt	Belt	Belt	Belt
HP	350	400	350	400	350	400

NR = Not Reported.

4.2.2.10 Auxiliary Design Considerations--

Maintenance--Recirculation pumps are often located in a limited space with difficult access, especially in retrofit installations. Since this large equipment must be dismantled periodically (typically at least every 18 months for inspection), the system design should facilitate maintenance. A winch-and-trolley system for moving heavy parts and ample space for dismantled components will simplify repairs. Some of the common malfunctions of slurry pumps and their most probable causes are listed in Table 4.2-2.

Housekeeping--Often the recirculation pump area is the most unsightly part of a scrubber facility. A constant stream of seal water, slurry, and oil leaks from the pumps, even in well-maintained systems. Therefore, the pump area should be designed for easy cleaning, with such features as sloping floors, wide (24-in.) floor trenches, and a good supply of water.

Expansion--Expansion joints on pump inlet and outlet piping are common sources of operating problems. When the joints fail, they can leak slurry under pressure (discharge side) or bleed air into the pump under vacuum (suction side). Proper specification, installation, and maintenance of expansion joints are important to pump performance.

Pump washouts--Since the circulating fluid is a slurry, solids will settle out of the liquid whenever the flow is stopped. If solids settle out in the pump, the pump impeller and lining can be damaged on startup. For this reason, a flush system that purges the pump with fresh water whenever the system becomes inoperative for extended periods is recommended.

Spare pumps--In order to achieve reliable operations, it is a practice to have spare equipment for the critical components of a lime FGD system. The degree of redundance (the number of spare pumps) for sluury recirculation pumps varies from 40 to 100 percent for the number of operating pumps. The number of spare pumps per scrubber should be specified by the design engineer. The stagnant slurry upstream from inlet and outlet isolation valves may lead to plugging. This can be minimized by keeping the spare pumps drained and by washing them frequently.

4.2.3 Performance Histories

Table 4.2-3 lists specifications of recirculation pumps installed at FGD facilities. The following is a brief summary of performance histories of lime slurry recirculation pumps.

Table 4.2-2. SLURRY RECIRCULATION PUMPS[11,12]
MALFUNCTIONS AND CAUSES

Malfunction	Causes
Pump develops less head and consumes less power over its whole working range, while efficiency remains unaltered	Deformed impeller casting, rotational speed lower than specified, undersized impeller
Head falls off rapidly with an increase flow rate while shutoff head is unchanged	Reduced throat area of the volute, reduced area between diffuser vanes
Flow rate is lower than rated by a constant amount at any given head	Worn wearing rings for closed impellers, worn wearplate or vanes for semiopen impeller
Head, capacity, efficiency, and horsepower are all lower over the entire range	Excessive clearance in the wearing rings, or between the vanes and wearplates
Head and efficiency are reduced, but horsepower is unchanged	Rough waterways in the impeller or casing (because of rust, scale, etc.)
Capacity drops off abruptly as head is reduced	Insufficient NPSH
NPSH requirements are higher at all flow rates	Worn seal rings, rough waterways

Table 4.2-3. SCRUBBER SLURRY RECIRCULATION PUMP SPECIFICATIONS - EXISTING FACILITIES[5,7,10,11,12,13]

Location	Plant rating, MW	No.	Pump vendor	Pump model	Individual pump capacity			Solids, %	Pump speed, rpm	Pump size, in.	Materials of construction
					Flow, gal/min	Head, ft	Motor, hp				
Phillips Duquesne Light	410	10	I-R	12 x 22 LP	9,000	100	350	12	1185	14 x 12 x 18	Stellited 317L SS
Green River Kentucky Utilities	64	3	I-R	400c	5,900	115	300	13	695	NR	Rubber-lined using HiCrome (28%) impellers
Conesville Columbus & Southern Ohio Electric	400	10	A-S-H	DG-9-5	9,544	90	400	9	450	16 x 16 x 39	Rubber-lined
Paddy's Run Louisville Gas & Electric	65	3	A-C	NR	6,000	140	450	10	~1000	12 x 16	Ni-Hard
Cane Run Louisville Gas & Electric	180	6	Denver	NR	5,800	100	300	10	1000	NR	Rubber-lined
Bruce Mansfield	835	12	A-S-H	DG-9-5	11,000	95	500	NR	≈500	16 x 16 x 39	Rubber-lined
Pennsylvania Power Company		12		DG-9-5	9,500	101					
Elrama Duquesne Light	510	10	I-R	12 x 22 LP	9,000	100	350	12	1185	14 x 12 x 16	Rubber-lined

NR - Not reported.

Phillips[8,9,10]--At Phillips Station of Duquesne Power and Light Co., Ingersoll-Rand pumps with Carpenter 20 casing and impellers were originally used. The Carpenter 20 parts were found unsuitable for scrubber slurry service. As a result of erosion, the impellers and wear rings required replacement every 3 to 6 months.

Phillips has undertaken an extensive program to test a number of alloys. It has tested such materials as Alloy 20, 317L SS, 26 percent CrFe, CD4MCu (a high-chrome, high-nickel alloy), titanium, Carborundum, and TAPCO iron in various combinations for construction of impeller and wear rings. In addition, several impellers were rebuilt with the wear areas hard-surfaced with Stellite (Haynes No. 6). As a result of this material testing program, Phillips has eliminated the less promising materials (titanium, TAPCO iron, and 26% CrFe), and has achieved definite improvements in service life with the stellited 317L SS impellers and Carborundum wear rings. At present, these materials have given over 4000 hours of service without any wear. Tests are currently in progress on several rebuilt CD4MCu impellers hard-faced with plasma spray coatings.

Green River[8,13]--Ingersoll-Rand pumps with rubber-lined impellers and casing were originally installed at the Green River Station of Kentucky Utilities.

The rubber has repeatedly peeled from the impellers and the lining was destroyed after only 4 months of service. Ingersoll-Rand is changing from a two-piece to a one-piece impeller design. Green River is experimenting with high-chrome (28%) metal impellers. Estimated life is 1 year.

Paddy's Run[8,14]--Allis-Chalmers' pumps with Ni-Hard casing and impellers were installed at Paddy's Run Station of Louisville Gas & Electric Co.

Paddy's Run reports no failures of pump materials after 12,000 operating hours. There is slight evidence of erosion, but no evidence of corrosion on the impeller or lining. This operation maintains a pH of about 6 at the scrubber outlet.

Bruce Mansfield[8,15]--A-S-H pumps with rubber impellers and lining were installed at the Bruce Mansfield Station of Pennsylvania Power Co.

The plant reports no failure due to wear or corrosion. Impellers and liners have been replaced because of damage from miscellaneous material (welding rods) going through the pump. Because the pumps are located under the scrubbers, with no facilities for hoisting the parts, repair is difficult.

Conesville[8,16]--A-S-H pumps with rubber impellers and lining were installed at the Conesville No. 5 Station of Columbus of Southern Ohio Electric Co.

Conesville reports no failures due to wear or corrosion. It has replaced the rubber lining because of damage from pieces of pipe going through the pump. There are five pumps per module, one of which was designed to be spare. In recent operations, only three pumps are used at full load.

Elrama[8,9,10]--Ingersoll-Rand pumps with Alloy 20 casing and impellers were originally installed at the Elrama Station of Duquesne Light Co.

Elrama has had severe pump problems similar to those at Phillips. At this station, the utility experimented with rubber-lined pumps. The first set of rubber-lined pumps, supplied by Ingersoll-Rand, failed after approximately 1000 hours. The manufacturer has indicated that the lining failure on the impellers was due to a faulty two-piece design and aged rubber. The new rubber-lined pumps, now being tested, are supplied by Worman.

Cane Run[8,14]--At the Cane Run Station of Louisville Gas & Electric Co., Joy Denver pumps with rubber-lined impellers and casings are used. The main problem has been leakage from the packing gland, which needs replacement every 3 months. The rubber lining has not been replaced for about 2 years, though it has shown some erosion.

REFERENCES

1. Karassik, I.S., et al. Pump Handbook. McGraw-Hill Book Co., New York, New York, 1976.
2. Neerken, R.F. Selecting the Right Pump. Chemical Engineering, April 3, 1978, pp. 87-98.
3. Dalstad, J.I. Slurry Pump Selection and Application. Chemical Engineering, April 25, 1977, pp. 101-106.
4. Dublin, J.H. Select Pumps to Cut Energy Cost. Chemical Engineering, January 17, 1977, pp. 137-139.
5. Reynolds, J.A. Saving Energy and Costs in Pumping Systems. Chemical Engineering, January 5, 1976, pp. 135-138.
6. Doolin, J.H. Pumping Abrasive Fluids. Plant Engineering, November 1972.
7. Private communication with J.H. Wilhelm, EIMCo Process Machinery Division of Envirotech, October 1977.
8. Laseke, B.A., Jr. EPA Utility FGD Survey: December 1977 - January 1978. U.S. EPA-600/7-78-051, Industrial Environmental Research Laboratory, March 1978.
9. O'Hara, R.D., and R.L. Nelson. Operating Experience at Phillips and Elrama Flue Gas Desulfurization Facilities. Second Pacific Chemical Engineering Congress, September, 1977 pp. 308-315.
10. Private communication with R.D. O'Hara and J. Mallone, Duquesne Light Company, February 1978.
11. Yedidah, S. Diagnosing Troubles of Centrifugal Pumps - Part II. Chemical Engineering, November 21, 1977, pp. 193-199.
12. Yedidah, S. Diagnosing Troubles of Centrifugal Pumps - Part I. Chemical Engineering, October 24, 1977, pp. 125-128.
13. Private communication with J. Beard and V. Anderson, Kentucky Utilities, February 1978.

14. Private communication with R. Van Ness, Louisville Gas and Electric, February 1978.

15. Private communication with D. Boston, Columbus and Southern Ohio Electric, February 1978.

16. Private communication with R. Forsythe, Pennsylvania Power Company, February 1978.

CONTENTS

4.3 OTHER PUMPS

Page

4.3.1 Introduction 4.3-1

4.3.2 Reagent Feed Pumps 4.3-1

- 4.3.2.1 Service Description 4.3-1
- 4.3.2.2 Typical Characteristics 4.3-3
- 4.3.2.3 Special Design Considerations 4.3-3
- 4.3.2.4 Performance Histories 4.3-3

4.3.3 Thickener Supernatant Pumps 4.3-3

- 4.3.3.1 Service Description 4.3-3
- 4.3.3.2 Typical Characteristics 4.3-4
- 4.3.3 3 Special Design Characteristics 4.3-4
- 4.3.3.4 Performance Histories 4.3-4

4.3.4 Thickener Underflow Pumps 4.3-6

- 4.3.4.1 Service Description 4.3-6
- 4.3.4.2 Typical Characteristics 4.3-6
- 4.3.4.3 Special Design Considerations 4.3-6
- 4.3.4.4 Performance Histories 4.3-6

4.3.5 Pond Water Return Pumps 4.3-8

- 4.3.5.1 Service Description 4.3-8
- 4.3.5.2 Typical Characteristics 4.3-8
- 4.3.5.3 Special Design Considerations 4.3-8

References 4.3-9

4.3 OTHER PUMPS

4.3.1 Introduction

This section presents design information on pumps, other than slurry recirculating pumps, that perform important functions in the lime scrubber systems by pumping slurry feed, thickener supernatant liquid, thickener underflow, pond water, and fresh water to the system.

4.3.2 Reagent Feed Pumps

In lime FGD systems, the lime solids are mixed with water in a slaker to form a slurry that mainly contains suspended calcium hydroxide [$Ca(OH)_2$]. The lime slurry is continuously pumped to the scrubber system, as required, to replenish the calcium ions that are discharged to the thickener as calcium sulfite and calcium sulfate. The reagent slurry is usually stored in tanks and transferred to the slurry recycle tanks by the slurry feed pumps.

Lime slurry is less erosive than scrubber recirculation slurry because of the absence of calcium sulfite, calcium sulfate, and fly ash. If grits are present, however, they will increase erosion because of their hardness and nonuniform particle size. Though pumping of lime slurry is not as severe a service, the basic design philosophy will be the same as for the recirculation pumps. The salient features of lime slurry pumps are discussed in this section.

4.3.2.1 Service Description--

The lime as received contains tramp materials, such as rocks, metal, and wood. Proper design and operation of the screening process and the slaker should remove these impurities so that they do not hamper operation of the feed pumps (Section 4.5, Slurry Preparation).

The slakers usually use freshwater. Hence, the lime slurry is not subject to buildup of corrosive ions, such as chlorides, that occurs in closed-loop systems. In addition, because the pH of the lime slurry is always highly alkaline, the slurry will not cause acid corrosion. Typical lime slurry feed conditions are presented below:

pH	12
Solids, wt. percent	15
Solids	$Ca(OH)_2$, $Mg(OH)_2$
Temperature, °F	120
Specific gravity	1.1

Table 4.3-1. LIME FGD SYSTEMS PUMP DATA - LIME SLURRY FEED PUMPS

Location/Utility	Manu-facturer	Model	Flow, gal/min, each	Head, ft	Pump speed, rpm	Drive	Materials		Motor, hp	No. of pumps
							Casing	Impeller		
Conesville No. 5 Columbus & Southern Ohio	Galigher	3-VRA-200	145-320	72	675	Hydraulic	Rubber lined	Rubber lined	20	3
Elrama Duquesne Light	Goulds Morris	1-1/2 JC-14	90	105	NR	Direct	Cast iron	Cast iron	15	6
Phillips Duquesne Light	Goulds Morris	1-1/2 JC-14	120	127	NR	Direct	Cast iron	Cast iron	15	5
Green River Kentucky Utilities	I-R	40 CIR	90	58	1550	Belt	Rubber lined	Rubber lined	5	2
Cane Run Louisville Gas and Electric	Joy Denver	NR	200	75	1800	Belt	Cast iron	Cast iron	10	2
Paddy's Run Louisville Gas and Electric	Worthington	ER-3729-2-1/2R091	100	60	1800	Direct	Cast iron	Cast iron	5	2
Bruce Mansfield Nos. 1 and 2 Pennsylvania Power	Joy Denver	SRL-2	300	98	875	Belt	Rubber lined	Rubber lined	125	4

NR - Not reported.

4.3.2.2 Typical Characteristics--

The lime slurry pumps are usually of centrifugal type with belt or direct drive. The impeller and casing may be plain cast iron, neoprene rubber, or hard-iron lined with natural rubber. The rubber lining is desirable if the grits removal system is not very effective.

4.3.2.3 Special Design Considerations--

Since slurry feed pumps are located near the base of the lime slurry tank, they are subjected to occasional dousing with lime slurry; therefore, the motor and drive housing should be enclosed in watertight casings to shield them from lime slurry.

Operation of the entire scrubber system depends on a constant supply of lime slurry. Design of the lime slurry supply system should, therefore, provide enough redundance to ensure scrubber reliability.

4.3.2.4 Performance Histories--

Design data for slurry feed pumps at existing lime FGD systems are presented in Table 4.3-1. Following is a summary of reported operating experiences:[1-5]

No major problems are reported in pump operations at Conesville, Green River, Phillips, and Elrama stations. The presence of excessive grits in the lime, however, has recently been a source of concern at the Conesville No. 5 unit. At Cane Run and Paddy's Run, the packing glands were initially too tight and had to be replaced. Recent operations have been trouble free.

Bruce Mansfield No. 1 unit required some modifications to the system. The rubber liners in the lime slurry feed pumps were damaged by cavitation. Baffle plates were installed over the pump suction opening in the scrubber vessels. This solved the problem, but several modifications of the baffles were required before one was found that could withstand the stresses and corrosive atmosphere.

4.3.3 Thickener Supernatant Pumps

Waste slurry is usually pumped to a thickener, where clarified liquid overflows and is pumped back to the scrubber system.

4.3.3.1 Service Description--

Although most solids are removed in the clarifier, the overflow may occasionally contain some suspended solids. The pH of the liquid is dependent on good pH control in the scrubber. Although the range of pH is normally 7 to 8, under upset conditions in the scrubber the pH may go down to 2. Since corrosive ions such as chlorides may build up in the liquid in a closed-loop operation, the main design consideration for wetted parts of the pumps is corrosion.

Following are typical properties of thickener overflow liquid:

pH	7 to 8 (normal)
Solids, wt. percent	1
Temperature, °F	130
Specific gravity	1.01

4.3.3.2 Typical Characteristics--

The thickener supernatant pumps are usually the centrifugal type with direct drive. The impeller and casing are commonly 316L SS, though at Cane Run and Paddy's Run pumps with rubber impellers and rubber-lined casings are used.

4.3.3.3 Special Design Considerations--

As with the lime feed pumps, operation of the scrubber system is dependent on continuous functioning of the thickener supernatant pumps. Systems should be designed with sufficient redundance to insure scrubber reliability.

Since these pumps are usually located outdoors in a remote area, instrumentation is needed for monitoring pump operation from the scrubber control room. In addition, protection is recommended at those locations where pumps may freeze when the scrubber is shut down.

4.3.3.4 Performance Histories--

Design data for thickener supernatant pumps at existing lime FGD systems are given in Table 4.3-2. Following is a summary of reported operating experiences:

At Conesville No. 5 the pumps have been operating satisfactorily with no reported problems.

At Elrama and Phillips the pumps were originally made of cast iron, which suffered severe corrosion because of the pH fluctuations caused by inadequate pH control. The present material (CD4M Cu) has given satisfactory service. The pumps at Cane Run and Paddy's Run were originally underdesigned. No problems have been reported after the capacity of the pumps increased.

Bruce Mansfield Nos. 1 and 2 pumps initially had vibration problems. The fiberglass reinforced plastic (FRP) piping was replaced by steel at the discharge end to reduce the noise level. In addition, an insufficient net positive suction head (NPSH) caused air entrainment and cavitation. The reclaimed water tank was raised by about 4 ft to alleviate this problem.

Table 4.3-2. LIME SCRUBBER PUMP DATA THICKENER SUPERNATANT PUMPS

Location/Utility	Manu-facturer	Model	Flow, gal/min,each	Head, ft	Pump speed,rpm	Drive	Materials		Motor, hp	No. of pumps
							Casing	Impeller		
Conesville No. 5 Columbus & Southern Ohio	Goulds Morris	NR	1080	240	NR	Direct	316	316	125	2
Elrama Duquesne Light	Goulds Morris	3175	1650	180	NR	Direct	CD4-M Cu	CD4-M Cu	125	3
Phillips Duquesne Light	Goulds Morris	3175	1650	180	NR	Direct	CD4-M Cu	CD4-M Cu	125	3
Cane Run Louisville Gas and Electric	Goulds Morris	3196	600	100	1800	Direct	Rubber lined	Rubber lined	25	2
Paddy's Run Louisville Gas and Electric	Allis Chalmer	912	250-300	120	1800	Direct	Rubber lined	Rubber lined	30	3
Bruce Mansfield Nos. 1 and 2 Pennsylvania Power	Goulds Morris	3175	6760	140	1180	Direct	316L	316L	300	4

NR - Not reported.

4.3.4 Thickener Underflow Pumps

The underflow from the thickener is pumped either to a dewatering system or to a sludge pond, which is often located several thousand feet from the thickener. Since the service is severe, proper specifications for these pumps are critical.

4.3.4.1 Service Description--

The thickener underflow is a thick slurry containing all the solids species present in the scrubber (calcium sulfate, calcium sulfite, fly ash, lime, etc.). If a centrifugal pump is to be specified, the concentration of solids in the thickener underflow will be limited to about 40 percent maximum because higher concentrations could not be pumped with a centrifugal pump without causing nonuniform flow. For thickener underflow containing more than 40 percent solids, positive displacement pumps are commonly used. Scrubber pH control is important so that these pumps will not be subjected, even intermittently, to high concentrations of corrosive ions. Because the slurry does contain high concentrations of abrasive solids, the main design consideration is erosion.

Following are typical thickener underflow characteristics:

pH	8 to 10
Solids, wt. percent	40
Solids	Fly ash, calcium sulfate, calcium sulfite
Temperature, °F	130

4.3.4.2 Typical Characteristics--

The thickener underflow pumps are either centrifugal or positive displacement type, with belt drive. For the centrifugal pumps, the impeller and casing lining material is rubber. If positive displacement pumps are used, it is recommended that the rotors be rubber lined and high alloys be used for stators. The positive displacement pumps should be designed to have a nonpulsating uniform flow.

4.3.4.3 Special Design Considerations--

The factors that influence the thickener overflow pumps also apply to the underflow pumps:

- Redundancy to insure scrubber reliability
- Controls for remote operation
- Protection against damage by freezing (if required)

4.3.4.4 Performance Histories--

The design data on thickener underflow pumps at existing lime FGD systems are given in Table 4.3-3. The following is a summary of reported operating experiences.[1-5]

Table 4.3-3. LIME SCRUBBER PUMP DATA - THICKENER UNDERFLOW PUMPS

Location/Utility	Manu-facturer	Model	Flow, gal/min,each	Head, ft	Pump speed, rpm	Drive	Materials		Motor, hp	No. of pumps
							Casing	Impeller		
Conesville No. 5 Columbus & Southern Ohio	Galigher	NR	460	100	NR	Hydraulic	Rubber lined	Rubber lined	40	2
Elrama Duquesne Light	Allen-Shermanhoff	A-6-5	200	65	NR	Belt	316L	Rubber lined	25	3
Phillips Duquesne Light	Allen-Shermanhoff	A-6-5	200	65	NR	Belt	316L	Rubber lined	25	3
Cane Run Louisville Gas and Electric	Robbins Myers	2XNG12H-CDR	200	115	1800	Variable	Neoprene rubber	Hi-A alloy, stator	20	2
Paddy's Run Louisville Gas and Electric	Allen-Shermanhoff	AA-6-5	150	120	1800	Belt	Rubber lined	Rubber lined	5	2
Bruce Mansfield Pennsylvania Power	Joy Denver	SRL-C	1500	70	700	Belt	Rubber lined	Rubber lined	75	4

NR - Not reported.

At Conesville No. 5 the centrifugal, rubber-lined pumps have been operating very well. At Elrama, the centrifugal pumps have enough capacity to handle the additional load from two or more thickeners. The Moyno (positive displacement) pumps at Cane Run have given excellent service. The thickener underflow line was replaced with one of larger diameter at Paddy's Run to reduce frictional losses. At Bruce Mansfield Nos. 1 and 2, the rubber lining of the centrifugal pumps is replaced about once a year.

4.3.5 Pond Water Return Pumps

Most of the lime FGD systems pump the pond water back to the system, which may be several thousand feet from the pond.

4.3.5.1 Service Description--

This water is similar to overflow water from the thickener. The only major problem is caused by buildup of corrosive ions such as chlorides in a closed-loop operation.

Typical characteristics of pond return water are presented below:

pH	6 to 8
Solids, wt. percent	0
Temperature, °F	70

4.3.5.2 Typical Characteristics--

The pond water pumps are centrifugal pumps with alloy steel impellers. The head developed by these pumps is generally about 200 ft H_2O.

4.3.5.3 Special Design Considerations--

These pumps also are usually located outdoors, several thousand feet from the scrubber control room. They therefore require equipment for remote control and for protection of material in freezing weather.

REFERENCES

1. Personal communication with D. Boston, Columbus and Southern Ohio Electric, February 1978.

2. Personal communication with J. Beard and V. Anderson, Kentucky Utilities, February 1978.

3. Personal communication with R. O'Hara and J. Mahone, Duquesne Light Company, February 1978.

4. Personal communication with R. Vanness, Louisville Gas and Electric, February 1978.

5. Personal communication with R. Forsythe and W. Norrocks, Pennsylvania Power Company, February 1978.

CONTENTS

4.4 LIME UNLOADING AND STORAGE CONTENTS

Page

4.4.1 Characteristics of Lime 4.4-1

4.4.2 Lime Transportation 4.4-6

  4.4.2.1 Truck Shipments 4.4-6
  4.4.2.2 Rail Shipments 4.4-8
  4.4.2.3 Barge Shipments 4.4-10

4.4.3 Unloading Design Criteria 4.4-12

  4.4.3.1 System Design 4.4-12
  4.4.3.2 Dry Lime Conveying 4.4-16
  4.4.3.3 Lime Storage and Feed Bins 4.4-19

4.4.4 Existing Facilities 4.4-22

  4.4.4.1 Receiving 4.4-22
  4.4.4.2 Storage 4.4-22
  4.4.4.3 Conveying 4.4-22
  4.4.4.4 Performance History 4.4-25

Appendix 1 4.4-26

References 4.4-28

4.4 LIME UNLOADING AND STORAGE

This section describes the design of lime unloading and storage facilities used in lime slurry scrubbing systems. It begins with bulk receipt and ends at the inlet to the lime feed mechanism, which itself is discussed in Section 4.5, Lime Slurry Preparation.

4.4.1 Characteristics of Lime

Lime is manufactured by heating crushed limestone to high temperatures (1652° to 2192°F). The process is known as calcining.

$$\underset{\text{limestone}}{CaCO_3} \xrightarrow{\text{heat}} \underset{\text{quicklime}}{CaO} + \underset{\text{carbon dioxide}}{CO_2} \uparrow \qquad \text{(Eq. 4.4-1)}$$

Lime manufacturers also react quicklime with water to form hydrated lime, primarily calcium hydroxide [$Ca(OH)_2$].

$$\underset{\text{quicklime}}{CaO} + \underset{\text{water}}{H_2O} \rightarrow \underset{\substack{\text{slaked lime} \\ \text{(calcium hydroxide)}}}{Ca(OH)_2} \downarrow \qquad \text{(Eq. 4.4-2)}$$

This is a bulk material that is easier to store and handle, but since it is more costly than quicklime, it is rarely used by large installations. About 4 lb of hydrated lime are needed to neutralize the same amount of acid neutralized by 3 lb of quicklime.

The National Lime Association, a lime manufacturing industry cooperative, recognizes six standard size classifications of quicklime (Table 4.4-1). These classifications are not binding to individual producers, however, who may adopt other definitions or sell other sizes. A "nonstandard" size, in fact, consisting of pebble lime screened or crushed to eliminate particles larger than about 1 in., is used by many utility lime scrubber installations.

The chemical composition of quicklime is determined primarily by the composition of the limestone rock from which it was made.[1] The most variable chemical constituent is the element magnesium. Geologic processes have caused carbonate rocks to be formed most often either with little magnesium (calcite), or with approximately equal molar amounts of calcium and magnesium carbonates (dolomite). Most commercial limes are therefore either "high-calcium," containing less than 5 percent MgO, or "dolomitic" lime, containing 35 to 45 percent MgO by weight. Lime made from a mixture of the two rocks, or from deposits

Table 4.4-1. STANDARD SIZES OF QUICKLIME[1]

Size	Description
1. Lump lime	Maximum size 8-in. diameter
2. Crushed or pebble lime	2 to 2-1/4 in. diameter
3. Granular lime	Product from fluidized-bed kilns; size range = 100% passing No. 8 sieve to 100% retained on No. 80 sieve
4. Ground lime	Obtained by grinding or screening larger sizes; size range = ~100% passing No. 8 sieve to 40-60% passing No. 100 sieve
5. Pulverized lime	Obtained by more intense grinding than for ground lime: size range = ~100% passing No. 20 sieve to 85-95% passing No. 100 sieve
6. Pelletized lime	Obtained by compressing quicklime fines into ~1-inch pellets or briquettes

with an uncommon magnesium content, has recently become popular, and the term "magnesian lime" has been accepted to define a product containing from 5 to 35 percent MgO by weight. The trade name "Thiosorbic" has also been coined to describe a magnesian lime containing between 5 to 10 percent MgO. Calcitic lime contains 0 to 5 percent MgO.

In addition to containing calcium and magnesium oxides, quicklimes consist of 1 to 10 percent of material that will not react with water. Generally called "grit," this material has two distinct portions: (1) sand and fused particles of iron and aluminum oxides or silicates, and (2) calcium and magnesium carbonates that were not converted into lime by calcining.

Table 4.4-2 lists the physical properties of good quality quicklime. The angle of repose (see Figure 4.4-1), it should be noted, varies with particle size distribution; a high proportion of fine particles increases the angle. Particle size is important in that pulverized quicklimes do not flow from a hopper as readily as coarser grades.

Quicklime does not corrode ordinary construction materials such as carbon steel, concrete, and most plastics. Nor is it especially abrasive, but it will cause a moderate amount of mechanical wear in bins and conveying equipment. Although quicklime is incombustible, high temperatures can develop if it accidentally contacts water or chemicals containing water of hydration.

Quicklime is hazardous and can burn the skin; it is particularly damaging to the eyes and, if dust is inhaled, to the throat and lungs. In areas where quicklime dust may be prevalent, workers should wear a lightweight filter mask and tight-fitting safety glasses. Additional protection is required to prevent contact with the skin, particularly in hot weather when workers are perspiring. Besides eye protection and respirators, workers exposed to quicklime dust should wear proper clothing: a long-sleeved shirt with sleeves and collar buttoned; trousers with legs down over shoes or boots, head protection, and gloves. It is also advisable to apply a protective cream to exposed parts of the body, particularly the neck, face, and wrists. First aid treatment is given in Appendix 1, at the end of Section 4.4.

Although quicklime is hazardous, hydrated lime presents no danger. Its dust is irritating if inhaled, but causes no lasting damage. Hydrated lime will not burn the skin, does not react with water, and will not reach high temperatures unless mixed with strong acids. Dry hydrated lime is a light, fluffy powder, not abrasive or corrosive to ordinary materials. Its most troublesome characteristic is its angle of repose. If the material is aerated and dry, it may flow almost like liquid,

Table 4.4-2. PHYSICAL PROPERTIES OF QUICKLIME[1]

Specific gravity	3.2 to 3.4
Bulk density (pebble lime)	55 to 60 lb/ft^3
Specific heat @ 25°C	0.20 Btu/lb
Angle of repose (pebble lime)	50° to 55°

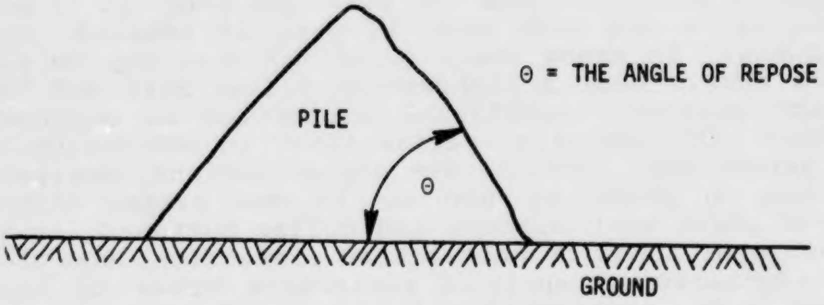

Θ = THE ANGLE OF REPOSE
PILE
Θ
GROUND

Figure 4.4-1. The angle of repose.

flooding through feeders and spilling over the edges of equipment. If the hydrated lime is compacted and slightly damp, the angle of repose may be as much as 80°, inhibiting steady flow from a hopper.

Before lime is fed to a lime scrubbing FGD system, it is slaked with water to form a slurry (Equation 4.4-2).

Any magnesium present in the quicklime will exist as a relatively stable double oxide, and two reactions can occur when water is added:

$$CaO \cdot MgO + H_2O \rightarrow Ca(OH)_2 \cdot MgO \qquad \text{(Eq. 4.4-3)}$$

$$CaO \cdot MgO + 2H_2O \rightarrow Ca(OH)_2 \cdot Mg(OH)_2 \qquad \text{(Eq. 4.4-4)}$$

All these reactions liberate large quantities of heat. A significant fraction of the energy added to quicklime by the calcining process is released in the reaction of quicklime and water.

All the reaction products have a very low solubility in water. Reaction products containing magnesium are even less soluble than limestone or gypsum.

Only under proper conditions, involving the right temperature, water-to-lime ratio, and degree of agitation, will quicklime react completely with water; under other conditions, a particle of quicklime will become surrounded by a layer of reaction products, thereby excluding water from contact with material in the center of the particle. Unreacted quicklime will therefore appear in the lime slurry and can cause erosive damage to slurry handling equipment.

The mechanism by which hydration reactions can be carried to completion has been studied extensively, primarily to allow users to optimize the "slaking" reaction, the reaction of quicklime in an excess of water. According to one theory, at optimum slaking conditions heat from the reaction converts water into steam at the surface of a quicklime pebble. The steam's expansion, plus agitation of the mixture, causes reaction products to be carried away from the surface of the pebble as they form, thereby exposing fresh surfaces for further reaction. This is further discussed in Section 4.5.

Electron micrographs have shown that hydrate structures in properly prepared lime slurry using either quicklime or hydrated lime are mostly in the form of very small needles, less than 1 μm in length. Such a slurry exposes a very large surface area to subsequent reactions, and is efficient in neutralizing acids. As particles increase in size, their reactivity drops rapidly in proportion to their surface area, even in concentrated acid.

4.4.2 Lime Transportation

Lime is transported from the manufacturers to the users in various ways. When very small quantities are involved, the most convenient method is to ship it in bags. In the quantities required for lime scrubbers, it is bought in bulk and transported in trucks, trains, or barges designed for handling bulk solids.

4.4.2.1 Truck Shipments--

The truck trailer most often used for transporting lime is a pressure-differential tank trailer or "blower truck" (Figure 4.4-2), which is manufactured by several companies. They are available with capacities of 12 to 25 tons. The trailer is virtually self-unloading, requiring only that the receiving bin be equipped to accept the pressurizing air and to control dust. The trailer is built as a tank with hopper bottoms. The hoppers connect through valves to a short manifold. For unloading, the manifold is connected with a hose to the customer's 4-in. pipe leading to a storage bin. The trailer is then pressurized to about 15 psi by a motor-driven compressor mounted on the truck. Additional air from the compressor is sent through the 4-in. pipe to the storage bin, and the valve is opened between one hopper and the manifold. Lime is blown from the tank into the manifold and is pneumatically conveyed through the pipeline into the bin. Tank pressure is adjusted to maintain an even flow of lime. When one hopper has emptied, the other hoppers in turn are opened into the manifold. When all hoppers are empty, the compressed air in the trailer blows into the storage bin. Pressure-differential trailers are usually equipped with aeration pads in the hoppers so they can also be used for hydrated lime. Pads are not usually needed to unload quicklime. The largest size of pebble lime that can be handled is 1-1/4 in., but a 1-in. top size is preferred to prevent plugging during unloading. Pebble lime can be blown as much as 100 ft vertically and 150 ft on a combined vertical and horizontal run. Greater distances are possible, but would involve excessive unloading times.

The self-loading and self-unloading hopper trailer is a more sophisticated version of the pressure-differential trailer. Although most often used to ship more expensive chemicals, trailers of this type are occasionally used for lime. They contain rotary feeders, pneumatic conveyors, and dust collection equipment. They require no supplemental equipment to transport bulk solids, nor do they need a bin dust collection mechanism.

Air-activated, gravity-discharge hopper trailers are also used to transport lime, particularly finer products such as pulverized quicklime and hydrated lime that are not normally used in scrubber facilities. These trailers have a single

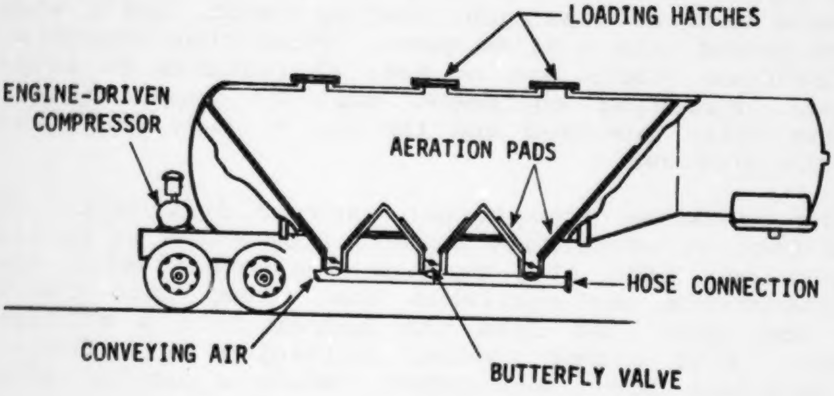

LOADING HATCHES
ENGINE-DRIVEN COMPRESSOR
AERATION PADS
HOSE CONNECTION
CONVEYING AIR
BUTTERFLY VALVE

Figure 4.4-2. Pressure-differential tank trailer.

outlet connection (Figure 4.4-3), and blow-through airlock feeders regulate the unloading rate. A low-power fan mounted on the trailer supplies air to aeration pads in the bottom of the tank to fluidize the lime and cause it to flow by gravity to the outlet. This type of trailer cannot elevate lime into a storage bin; the customer must supply a mechanical or pneumatic conveyor for this purpose.

4.4.2.2 Rail Shipments--

Most rail shipments of lime are made in standard covered hopper cars (Figure 4.4-4). Originally designed to handle cement, these cars are used for any solid material that must be protected from rain. They can hold about 100 tons of quicklime. The cars are built with two to four separate rectangular compartments, each with at least one loading hatch, and a sloping hopper bottom closed with a slide gate. Other than brackets for attaching vibrators, there are no special features to simplify unloading; all unloading equipment must be supplied by the customer. The costs involved and the car's ready availability account for its wide use.

Unloading quicklime from hopper cars is difficult. Often it is dumped into an undertrack hopper, from which it is transported by conveyor into storage bins. Alternatively, vacuum unloading attachments are available that clamp onto the discharge gate and suck lime from the hopper into a storage or transfer tank. With either system, unloading is a dusty and relatively hazardous job. Avalanches inside a partly unloaded hopper can cause lime to spill from open hatches. Lime tends to hang in corners and must be knocked down with poles from the top of the car. Fabric chutes are often used during gravity unloading to minimize dusting, but they are not very effective. Placement of the gates makes it difficult to attach suction equipment; if the car has worn springs, it may have to be jacked up before the attachments will fit. The unloading crew may also have to use a car puller to position the car so that all hoppers can be unloaded.

Railroad cars that are much easier to unload are in wide use, but are available only by lease arrangements with their owners. Unless the car can be kept busy, the cost may be too high to warrant its use. Two cars that are the rail equivalents of the truck trailers described earlier are also in use for lime hauling. One of these is a pressure-differential tank car, which consists of three or four cylindrical pressure vessels with hopper bottoms permanently mounted on a flat car. Each tank holds about 15 tons of quicklime. An aeration pad and an outlet pipe are installed in the bottom of each hopper. The unloading operation is identical to that described for the pressure-differential truck trailer, except that air pressures are higher and air must be supplied from a stationary source at

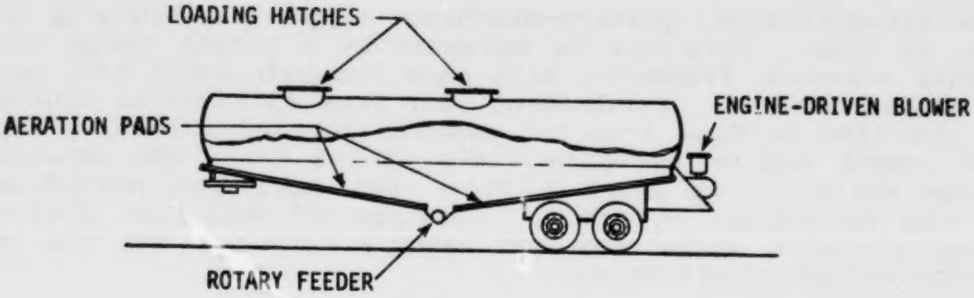

LOADING HATCHES
AERATION PADS
ENGINE-DRIVEN BLOWER
ROTARY FEEDER

Figure 4.4-3. Hopper trailer with air-activated, gravity-discharge hopper.

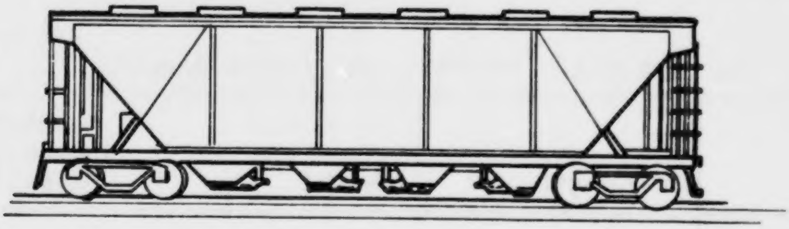


Figure 4.4-4. Covered hopper car.

the unloading station. With this car, lime can be blown over longer distances and into higher storage bins than can be achieved with the blower truck.

The air-activated, gravity-discharge hopper car hauls up to 45 tons of lime. This car is essentially a single large bin built into a boxcar framework with aeration pads built into the hopper-shaped bottom. In unloading, air from an external source causes the lime to flow from two outlets located halfway along the car length and on opposite sides of the car. The outlets clear the rails by at least a foot, and dustproof unloading chutes can be easily attached. Aeration of the lime during unloading prevents avalanches and hangups; one man can easily handle the unloading operation.

4.4.2.3 Barge Shipments--

Barge transport of lime is common in this country. Many truck shipments, in fact, are unloaded from barges at central points for distribution to users who are not near navigable waterways. Operators of a large lime scrubber, properly located, may realize substantial savings by directly purchasing lime in barge quantities.

The craft used for lime transport is a hopper or covered barge, built with a separate hold inside the framing of the hull. The deck is waterproof and is fitted with waterproof hatch covers. For use on inland waterways, hopper barges have shallow drafts and are approximately square ended, with a long bow rake and a shorter stern rake. Three standard sizes are in use, built to fit efficiently into standard river locks (Table 4.4-3). Similar vessels are built for marine service.

Table 4.4-3. COVERED OR HOPPER BARGES

Barge type	Length, ft	Width, ft	Approximate pebble lime capacity, tons
Pittsburgh	175	26	800
Jumbo	195	35	1200
Large	240	40-50	2000

Barge transport requires substantial investment in dock facilities that cannot usually be justified for lime handling alone. A typical barge-unloading installation with vacuum gear is shown in Figure 4.4-5. Most scrubber operators using barged lime add the equipment to existing coal docks; separate equipment is usually needed to prevent intermixing of products and to keep the lime dry.

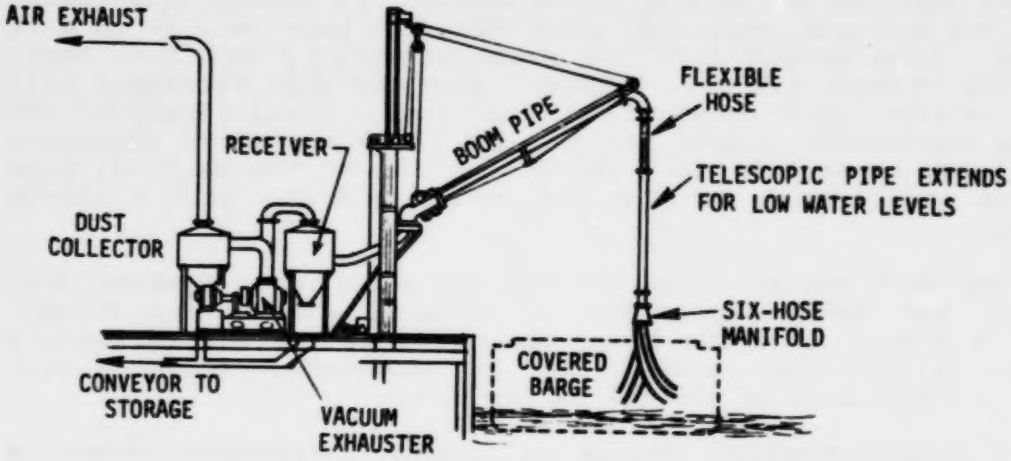

AIR EXHAUST
FLEXIBLE HOSE
BOOM PIPE
RECEIVER
TELESCOPIC PIPE EXTENDS FOR LOW WATER LEVELS
DUST COLLECTOR
SIX-HOSE MANIFOLD
COVERED BARGE
CONVEYOR TO STORAGE
VACUUM EXHAUSTER

Figure 4.4-5. Vacuum barge unloading.

4.4.3 Unloading Design Criteria

4.4.3.1 System Design--

It is essential that any plant using bulk lime should include facilities to receive shipments by blower truck. Even if rail or barge is to be the principal mode of lime transport, truck shipments will probably be needed to supplement the supply, or to compensate for late deliveries. At least one lime storage bin, with a capacity of at least 1500 ft^3, should be fitted with inlet piping, a dust collector, and a pressure relief device.

The pneumatic pipe through which lime is transferred to the bin should be ordinary 4-in. carbon steel pipe, preferably with no more than one 90° change of direction. To reduce flow resistance and minimize wear, the pipe should be bent on a 3- to 4-ft radius. Lime should first be blown vertically and then horizontally (Figure 4.4-6). Greatest wear and most blockages will occur in pipe bends ahead of vertical runs. Total length of the piping should not exceed 150 ft, and total change of elevation should not exceed 100 ft. The bottom end of the vertical pipe section should be 4 ft from the ground and end with a 150-lb flange.

The dust collector on the bin may be a small cyclone collector, but better operation is obtained with a bag filter. Since a blower truck delivers about 750 ft^3 of air per minute and an air-to-cloth ratio of 2.0 is recommended for this service, a cloth area of 375 ft^2 is required.

A pressure-relief device is needed to prevent excessive pressure in the bin. A manhole with hinges and gaskets is frequently used. Pressure relief is needed especially at the end of an unloading operation, when all the compressed air in the trailer is exhausted into the bin. The final blast of air serves to clear lime from the transfer line, but usually overloads the capacity of the dust collector. If dust from the final blast is troublesome, the cloth area of the filter must be increased somewhat to about 650 ft^2.

Blower truck facilities are the most elementary facilities suitable for lime unloading. In initial scrubber design, it is wise to allow for future use of rail or barge delivery. The ability to accept larger loads greatly increases the number of possible suppliers and thus may effect considerable cost savings.

Rail deliveries in standard covered hopper cars can be unloaded either by an undertrack hopper or a vacuum-unloading installation, depending on climate and topography. If the region is hilly and if a spur track can be built into the side of a hill, an undertrack hopper can often be designed with

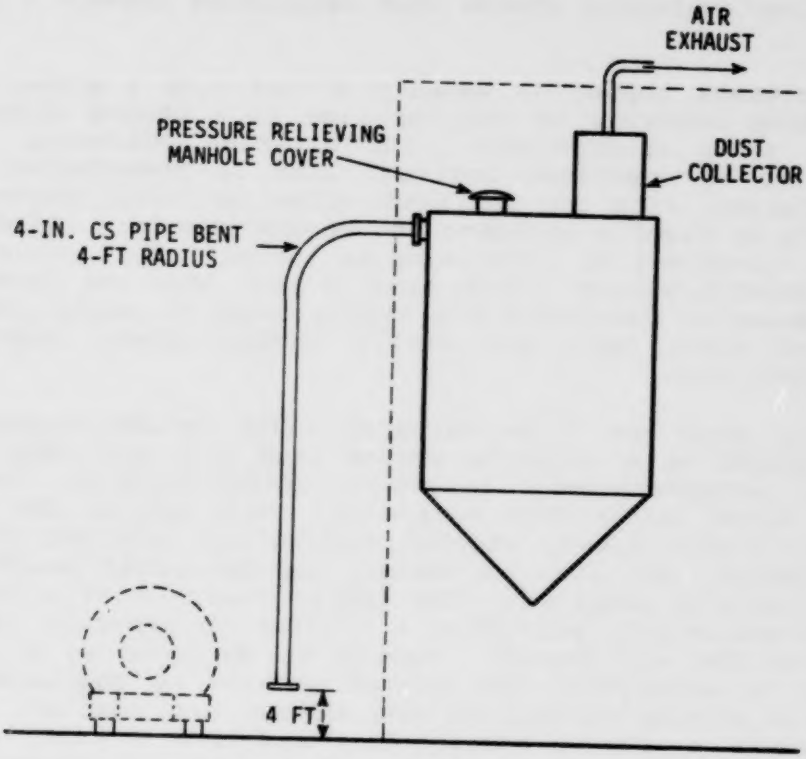

AIR
EXHAUST
PRESSURE RELIEVING
MANHOLE COVER
DUST
COLLECTOR
4-IN. CS PIPE BENT
4-FT RADIUS
4 FT

Figure 4.4-6. Blower truck receiving bin.

sufficient drainage and air circulation to keep the lime and equipment dry. In a flat area with a high water table and frequent humid weather, the vacuum unloading system, although often more expensive to construct, is usually the better choice.

Gravity unloading of rail cars requires a spacious, weatherproof building. At least 12 ft of clearance is required above the car, and building heat is desirable to dehumidify the air during wet weather. The building must be well ventilated to capture lime dust, and the air should be kept dry during unloading by a recirculating system that ventilates through a dust filter.

The undertrack hopper is usually fitted with a screw conveyor or a drag conveyor to deliver lime to a bucket elevator for transfer to a storage bin. For hillside unloading, the bucket elevator is sometimes omitted; lime is transferred directly to storage with an inclined screw or drag conveyor. Conveyors must be tightly enclosed and weatherproofed, and often must also be contained in a building or tunnel. Belt conveyors are usually unsatisfactory, since lime is lost into the conveyor housing. Pneumatic conveyors are rarely used to empty undertrack hoppers since they are easily choked unless separate feeders are provided.

If hopper cars are to be unloaded under vacuum, equipment is usually bought as a complete system from a single supplier. Several U.S. manufacturers, including Sprout-Waldron, Buell, Fuller, and Ducon, offer this equipment. With any of the systems shown in Figure 4.4-7, adapter devices are attached to the car outlet gates, and lime is sucked through metal hoses and steel piping into a receiver. The latter consists of a vacuum tank, a dust collector, and often a cyclone to separate larger particles from the air stream. Vacuum is supplied by a large suction pump or exhauster; the unloading rate is regulated by bleeding in a stream of air at the hopper car adapter. The receiver is mounted above a storage bin, and lime is continuously emptied from the vacuum tank through an air-lock mechanism. Other conveyors may distribute the lime to several bins. In vacuum unloading, particles move at high velocity (3000 to 7500 ft/min) and there is some degradation of pebble size. Air volume ranges from 10 to 20 ft^3/lb of lime. There is usually less than 5 psi of vacuum at the exhauster suction. A building or shed is needed to allow unloading in wet weather, but vacuum unloading creates less dust than gravity unloading and ventilation requirements are therefore less severe.

Gravity-unloading hopper cars can be accommodated with either an undertrack hopper or a vacuum unloading system if the required adapters are purchased.

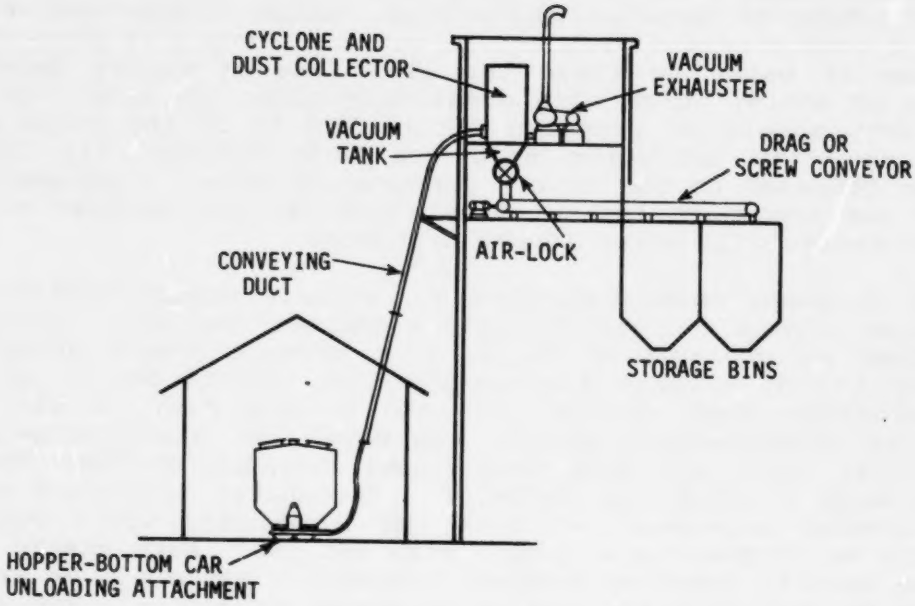

CYCLONE AND DUST COLLECTOR
VACUUM EXHAUSTER
VACUUM TANK
DRAG OR SCREW CONVEYOR
AIR-LOCK
CONVEYING DUCT
STORAGE BINS
HOPPER-BOTTOM CAR UNLOADING ATTACHMENT

Figure 4.4-7. Vacuum railcar unloading.

4.4.3.2 Dry Lime Conveying--

Until now we have dealt solely with unloading, which is simply a specialized application of conveying. Many lime scrubbing FGD systems, however, include conveyors other than unloading devices to transport lime into feed bins or from transfer bins into storage.

The most difficult in-plant conveying of dry lime occurs when the scrubber is a considerable distance from the unloading point. In such cases, a first thought is to prepare lime slurry near the unloading station and pump the finished slurry to the scrubber. This is usually impractical, since slurry that remains in a long pipeline will settle out and eventually plug the line. Use of water to rinse the line free of slurry causes formation of scale, which also eventually plugs the line. As a rule, slurry should be prepared within 200 ft of the point of use; if the lime unloading point is more distant, dry lime should be conveyed to the slurry preparation area. A pneumatic conveyor can transport lime at least 1000 ft, and several conveyors in series will cover longer distances.

Most in-plant conveying, however, entails simple elevation of the lime from a storage bin into a smaller feed bin. Figure 4.4-8 shows an application in which a screw conveyor accepts lime from one of several storage bins and discharges it to a bucket elevator that carries it into a feed bin. A simple combination of mechanical devices can move lime from storage at less initial cost and with less power consumption than that entailed with a pneumatic conveyor. Mechanical conveying requires careful arrangment of bins and equipment, which would preferably be aligned in a single straight row. Each change of direction usually requires another conveyor. Since pan or drag conveyors do not plug as readily as screw conveyors, they are preferred for long runs and for handling coarse grades of quicklime. Belt conveyors generally lose too much material into the housing to be considered suitable for quicklime service.

As conveying distances or elevations increase, or if conveyance involves several changes of direction or multiple points of delivery, the economic advantage of pneumatic conveying increases rapidly. Unlike those of a mechanical conveyor, the basic components of a pneumatic system are similar regardless of distance or elevation. They differ only in the length of piping and the size of the compressor and motor. Figure 4.4-9 shows a simple dry lime transfer by the pneumatic conveying principle.

This illustration also shows one of the two basic types of pneumatic conveyors, usually called the positive-pressure type. Lime is blown up the inclined pipe by the force of air from the compressor. The other basic conveyor type is the vacuum, or negative-pressure, system already referred to. It sucks lime through the pipe by means of a vacuum exhauster attached to the

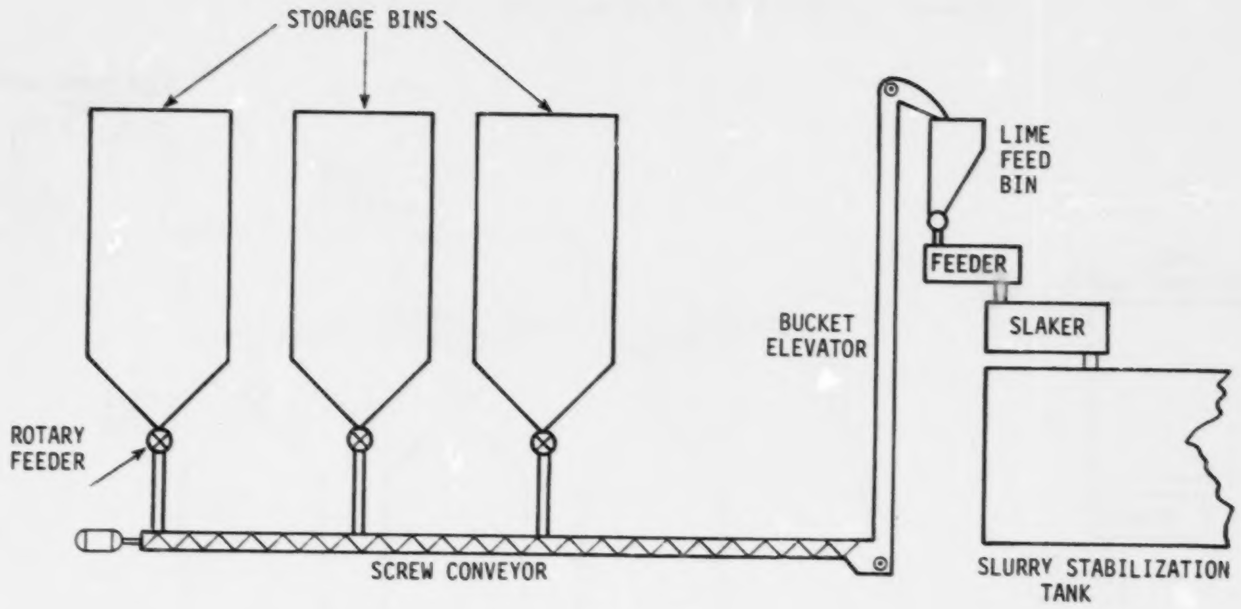

STORAGE BINS
LIME FEED BIN
FEEDER
BUCKET ELEVATOR
SLAKER
ROTARY FEEDER
SCREW CONVEYOR
SLURRY STABILIZATION TANK

Figure 4.4-8. Mechanical conveyors.

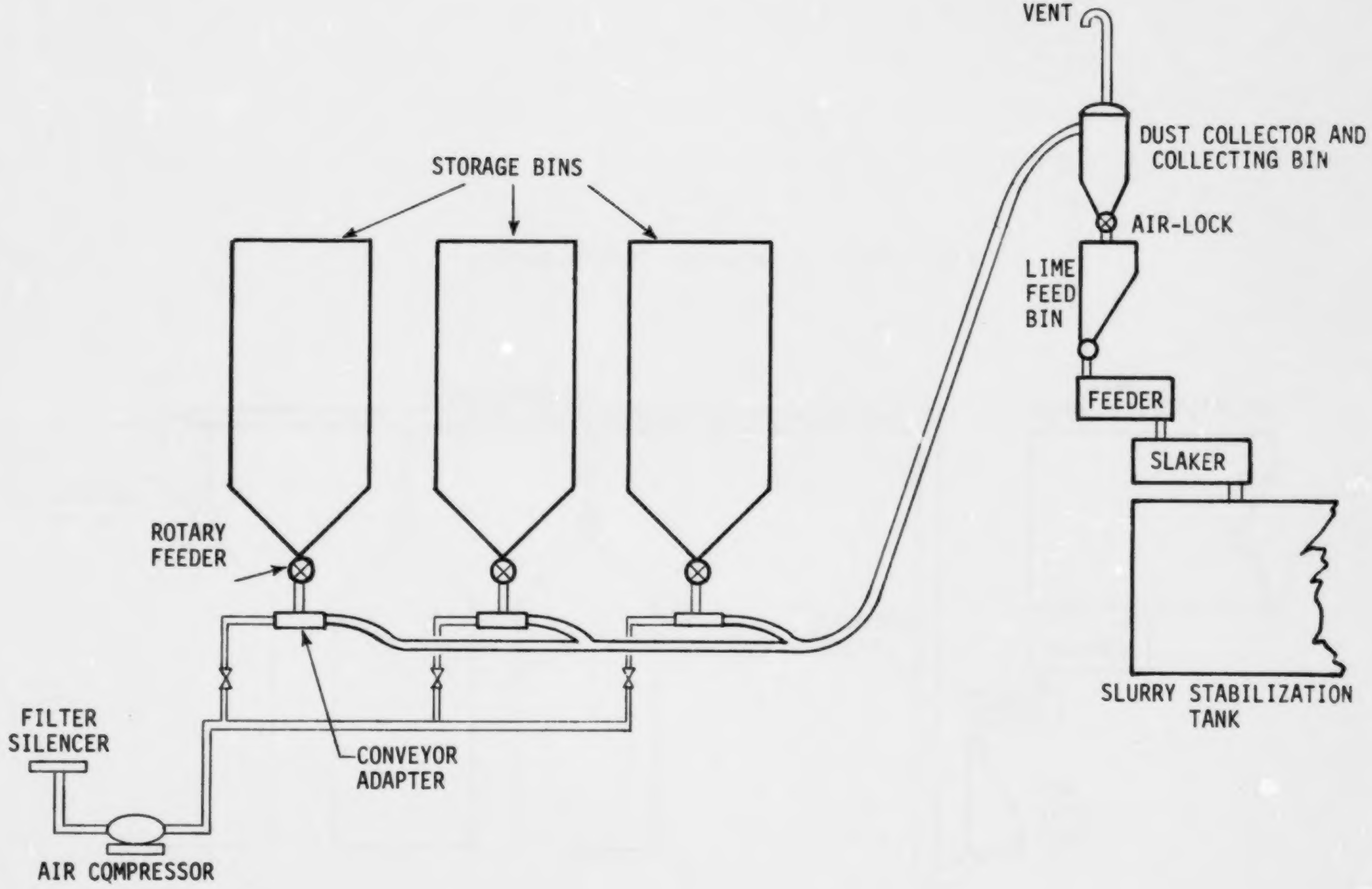

VENT
DUST COLLECTOR AND
COLLECTING BIN
STORAGE BINS
AIR-LOCK
LIME
FEED
BIN
FEEDER
SLAKER
ROTARY
FEEDER
SLURRY STABILIZATION
TANK
FILTER
SILENCER
CONVEYOR
ADAPTER
AIR COMPRESSOR

Figure 4.4-9. Positive-pressure pneumatic conveyor.

dust collector. The positive-pressure system has the advantages of atmospheric pressure in the receiving bin and a slight reduction in air flow rate due to higher air density. The negative-pressure system causes no condensation of moisture inside the pipeline and offers an equipment package with all system components close together. Both systems have the disadvantage of using air on a once-through basis, bringing large quantities of humid outdoor air into contact with the lime.

Another arrangement, usually called a closed-loop system, is shown in Figure 4.4-10. A single charge of air is recirculated from the compressor to the conveyor and back. A minimum amount of fresh air is drawn in, and the original charge remains dry. The closed loop can be constructed as either a positive-pressure or a vacuum system. This depends on the location of the loop vent, where atmospheric pressure is maintained. In Figure 4.4-10 (an example of a positive-pressure system) the loop vent is located at the feed bin to which lime is delivered. The closed-loop system offers the advantages of both the pressure and the vacuum conveyor, plus elimination of moisture. Its disadvantages include higher piping cost and greater power consumption.

The pneumatic conveyor with the lowest initial cost is a vacuum system in which the vacuum is produced by steam eductors. However, these should not be used to handle materials such as quicklime that are hazardous when contacted with water.

4.4.3.3 Lime Storage and Feed Bins--

In designing lime storage bins, the main consideration should be capacity. Failure to provide ample storage is usually the result of the assumption that lime deliveries will be constant and unvarying. In practice, truck shipments are frequently delayed by bad weather or breakdowns, and rail or barge shipments are even less predictable. Minimum bulk storage capacity for a constantly operating industrial facility is generally considered to be either 150 percent of a plant's normal shipment size, or capacity for 7 days' usage, whichever is larger. Better practice in a lime scrubber is to provide twice this volume, since lime is often transported on a less-dependable schedule than other, more-expensive, bulk chemicals.

The storage unit most often used for lime is a steel silo with a cone bottom. Cylindrical vessels hold the most material for a given weight of steel, but square, rectangular, and hexagonal bins are also used, and can be clustered to share common walls and thus save ground space. Concrete storage bins have been used in large installations and are often less expensive than steel bins. The schedule for commissioning a scrubber may preclude use of concrete, however, since concrete must "cure" for several months after construction before being used to store quicklime.

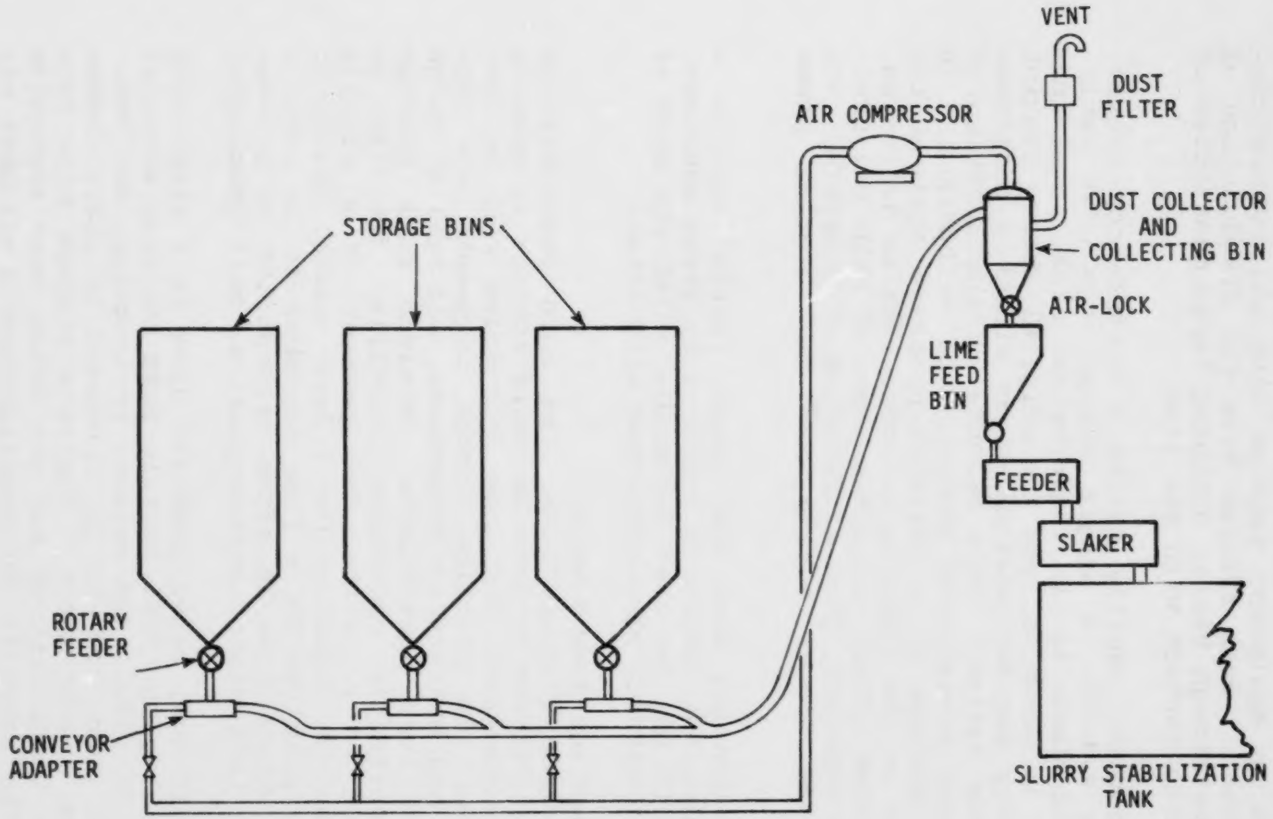

VENT
DUST FILTER
AIR COMPRESSOR
DUST COLLECTOR AND COLLECTING BIN
AIR-LOCK
STORAGE BINS
LIME FEED BIN
FEEDER
SLAKER
ROTARY FEEDER
CONVEYOR ADAPTER
SLURRY STABILIZATION TANK

Figure 4.4-10. Closed-loop pneumatic system.

Lime storage bins must be weatherproof and airtight to prevent absorption of water and carbon dioxide from the atmosphere. Attempts to use corrugated metal silos to store lime have been unsuccessful, since these silos are not sufficiently weatherproof for this service.

Storage bins must be fitted with a cone-shaped or hopper-shaped bottom to allow an even first-in/first-out flow of lime. Steel is most often used for the hopper section, even in concrete bins, to reduce sliding friction. In a steel cone free from fabrication edges, quicklime usually slides on a 45-deg slope. Where the hopper is made of a rough material such as concrete, a steeper angle is necessary; a pitch of 3:4 is usually satisfactory. Storage bins for hydrated lime require 60-deg cone bottoms.

The number of storage bins and their relative size and proportion are determined by construction economy. Economy usually increases with bin height and diameter, to the point where the bin becomes so large its initial transportation cost would be excessive. A diameter of 12 ft is often the most economical, with a maximum height of 40 ft. A bin of these dimensions will hold about 100 tons of quicklime.

The interior of a bin should not be painted. Protection against corrosion is unnecessary, notwithstanding the fact that abrasion from quicklime will remove any paint that is applied. Abrasion will polish the metal of a bin, especially near the outlet spout, but will not grind away sharp corners or weld spatter. Before a bin is placed in service, the area near the outlet should be ground smooth. It is undesirable to grind or polish the upper vertical walls of a bin. Roughness in the vertical surfaces may help to support the bin contents and therefore minimize packing in the hopper section.

With pebble quicklime, special bin unloading attachments are not usually required. As a precaution, attachments for portable vibrators are sometimes installed on the hopper section. Storage of pulverized quicklime usually justifies a permanently installed vibrator; in a large bin, a static type of antipacking device, such as that which discharges a volume of high-pressure air to dislodge a mass of lime, may be desirable. For hydrated lime, antipacking and flow assistance attachments are virtually a necessity. There is a wide variety of devices; no single type has proved superior for use with hydrated lime.

A lime storage bin may be connected directly to a lime feeder that meters a flow of lime into a slaker. Frequently, however, lime is transferred from a storage bin into a smaller feed bin at a higher elevation. Feed bins are usually more carefully designed than storage bins, since smooth flow to the lime feeder is important in achieving trouble-free performance of the lime slurry preparation equipment.

Lime feed bins are often designed to hold enough lime to permit either 10 or 26 hours of scrubber operation at maximum rate, so that they can be routinely filled once a shift or once a day. The hopper usually has a 60-deg slope; in addition, offset hoppers are often used. The problem with concentric hoppers on cylindrical bins is that "arches" or "domes" can form as material is withdrawn (Figure 4.4-11). If an arch forms, the operator must break it to restore flow. Formation of arches can be prevented by constructing the hopper as an unsymmetrical cone in which one edge is vertical (Figure 4.4-11). The offset construction is more expensive than a concentric design and wastes space. Use of offset hoppers on large storage bins usually cannot be justified; however, the extra expense may be warranted for one or two relatively small feed bins.

A rotary or slide-type shutoff gate is needed at the bottom of a feed bin, or any bin that connects to a lime feeder, to permit maintenance of the feeder without emptying the bin. As a service to the customer, dry feeder manufacturers will usually resell a suitable gate or one may be purchased separately.

4.4.4 Existing Facilities[2-6]

Data from utility lime scrubber systems are summarized in Table 4.4-4 and detailed below.

4.4.4.1 Receiving--

Four plants receive Thiosorbic quicklime in 1-3/4 in. top size. One plant, Bruce Mansfield, receives the material by barge;[6] the other three receive it by truck.

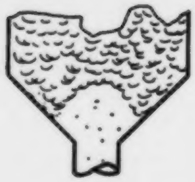
The two plants in Louisville, Kentucky, Cane Run and Paddy's Run, purchase hydrated lime from a carbide plant. Since the material arrives in a 30-percent solids slurry, these plants do not have dry lime handling equipment. Green River is the only plant currently receiving lime in rail cars. Note that the top size of Thiosorbic lime is larger (approximately 1-3/4 in.) than that of the other types (approximately 3/8 to 3/4 in.).

4.4.4.2 Storage--

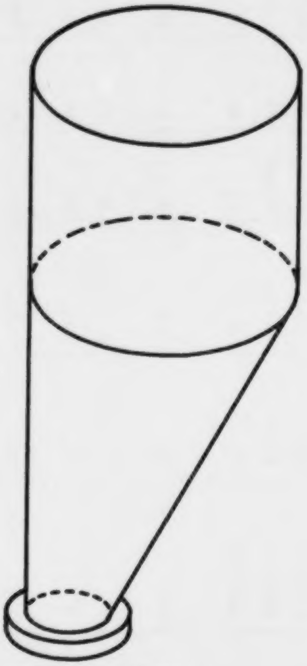
All facilities store lime in carbon steel silos except Conesville, where concrete is used. Two plants, Phillips and Elrama, are constructing three carbon steel silos. Storage capacity on full-scale plants ranges from 10 to 30 days. Green River, which has a 10-day supply, has shut down occasionally because of lime shortages.

4.4.4.3 Conveying--

Belt and pneumatic systems are both used in existing facilities. The belts are used on larger sizes of lime with relatively long runs; pneumatic conveyors are used for the shorter runs.



(a) SCHEMATIC OF ARCH FORMATION IN A CONCENTRIC HOPPER



(b) OFFSET HOPPER CONSTRUCTION

Figure 4.4-11. Feed bin design.

Table 4.4-4. EXISTING FACILITY DESIGN SPECIFICATIONS

Plant	Conesville No. 5	Four Corners No. 5A[a]	Bruce Mansfield Nos. 1 and 2	Mohave 1A[a]	Green River Nos. 1, 2, and 3	Cane Run No. 4	Paddys Run No. 6	Phillips	Elrama
Receiving									
Type of lime	Quicklime, Thiosorbic	Quicklime, high calcium	Quicklime, Thiosorbic	Quicklime, high calcium	Quicklime, high calcium	Hydrated lime	Hydrated lime	Quicklime, Thiosorbic	Quicklime, Thiosorbic
Top size, in.	1-3/4	3/8	1-1/2	3/8	3/4	NA	NA	1-3/4	1-3/4
Normal method	Truck	Truck	Barge	Truck	Railcar	Barge	NA	Truck	Truck
Size or receipt, tons	25	25	1000-1500	25	70	NA	NA	25	25
Storage									
Capacity of silos, tons (each)	11,500	300	4500	30	500	NA	NA	NR[b]	NR[b]
Number of silos	2	1	4	1	1	NA	NA	3	3
Storage capacity at design flow days	60[c]	30	22[d]	14	10	NA	NA	NR	NR
Material of construction	Concrete	C.S.	C.S.	C.S.	C.S.	NA	NA	C.S.	C.S.
Conveying									
Type	Belt	Pneumatic, blower	Belt	Pneumatic, blower	Pneumatic, vacuum	NA	NA	Pneumatic, blower	Pneumatic, blower
Distance, ft	300	NR	1500	80	75	NA	NA	70	70
Elevation change, ft	150	100	-100	-50	73	NA	NA	NR	NR

[a] FGD system no longer operational.
[b] Currently building silos.
[c] 30 days when Unit 6 starts up.
[d] 15 days when Unit 3 starts up.

NR - Not reported.
NA - Not applicable.

Reproduced from best available copy.

4.4.4.4 Performance History--

No problems have been reported in lime handling systems.

APPENDIX 1

First Aid Treatments for Calcium Oxide (Lime) Splashes[7]

Splashes of the skin

1. Flood the splashed surface thoroughly with large quantities of running water and continue for at least 10 minutes, or until satisfied that no chemical remains in contact with the skin. Removal of splashes with solvents, solutions, and chemicals known to be insoluble in water will be facilitated by the use of soap.

2. Remove all contaminated clothing, taking care not to contaminate yourself in the process.

3. If the situation warrants it, arrange for transport to hospital or refer for medical advice to the nearest doctor. Provide information to accompany the casualty on the chemical reponsible and brief details of the first aid treatment given.

Ingestion

1. If the chemical has been confined to the mouth give large quantities of water as a mouth wash. Ensure the mouth wash is not swallowed.

2. If the chemical has been swallowed give copious drinks of water or milk to dilute it in the stomach.

3. Do not induce vomiting.

4. Arrange for transport to hospital. Provide information to accompany the casualty on the chemical swallowed with brief details of the treatment given and if possible an estimate of the quantity and concentration of the chemical consumed.

Splashes of the eye

1. Flood the eye thoroughly with large quantities of gently running water either from a tap or from one of the eyewash-bottles provided and continue for at least 10 minutes.

2. Ensure the water bathes the eyeball by gently prying open the eyelids and keeping them apart until the treatment is completed.

3. All eye injuries from chemicals require medical advice. Arrange transport to hospital and supply information to accompany the casualty on the chemical responsible and brief details of the treatment already given.

REFERENCES

1. Lime Handling, Application, and Storage. Bulletin 213, National Lime Association, Washington, D.C. Third Edition. May 1976.

2. Personal communication with D. Boston, Columbus and Southern Ohio Electric, February 1978.

3. Personal communication with J. Beard and V. Anderson, Kentucky Utilities, February 1978.

4. Personal communication with R. O'Hara and J. Mahone, Duquesne Light Company, February 1978.

5. Personal communication with R. VanNess, Louisville Gas and Electric, February 1978.

6. Personal communication with R. Forsythe and W. Norrocks, Pennsylvania Power Company, February 1978.

7. Hazards in the Chemical Laboratory. G.D. Muir, ed. The Chemical Society, London, England. Second Edition. 1976.

CONTENTS

4.5 LIME SLURRY PREPARATION

Page

4.5.1 Introduction 4.5-1

4.5.2 Dry Lime Feeding 4.5-3

- 4.5.2.1 Introduction 4.5-3
- 4.5.2.2 Volumetric and Gravimetric Feeders 4.5-3
- 4.5.2.3 Available Equipment 4.5-6
- 4.5.2.4 Existing Facilities 4.5-9

4.5.3 Lime Slurrying (Slaking) 4.5-10

- 4.5.3.1 Introduction 4.5-10
- 4.5.3.2 Service Description 4.5-10
- 4.5.3.3 Available Equipment 4.5-12
- 4.5.3.4 Water Requirements for Slaking 4.5-17
- 4.5.3.5 Existing Facilities 4.5-18

4.5.4 Slurry Stabilization and Storage 4.5-18

- 4.5.4.1 Introduction 4.5-18
- 4.5.4.2 Service Description 4.5-18
- 4.5.4.3 Existing Facilities 4.5-23

References 4.5-31

Bibliography 4.5-32

Glossary 4.5-33

4.5 LIME SLURRY PREPARATION

4.5.1 Introduction

This section of the Lime FGD Systems Data Book presents design information on the process from the dry lime feeder through the slurry preparation system to the lime slurry feed pump. The receipt, storage, and conveying of dry lime through the inlet of the dry lime feeder mechanism are discussed in Section 4.4, the slurry feed pump in Section 4.3.

Preparation of lime slurry involves three steps:

1. Feeding dry lime to the system.
2. Reacting lime with water (slaking).
3. Stabilizing and storing the lime slurry.

These functions must operate as an integrated system to supply lime to the FGD system. The slurry is added to the scrubbing system at a rate normally controlled by the pH of the absorber liquor, and the system should also be designed to maintain a readily available supply of slurry in storage tanks. Consequently, when the slurry in the storage tank falls to a specified level the necessary equipment must be activated to produce slurry at a rate at least equivalent to that of maximum usage and preferably at an even higher rate to assure a sufficient inventory of lime slurry that will allow time for any maintenance of lime feeding equipment. The slurry feed rate control system can be designed for manual operation, which would require regular attention by an operator, or could be controlled semiautomatically, relieving the operator of much of the responsibility.

A suggested arrangement of equipment and instrumentation in a semiautomatic lime slurry preparation system is shown in Figure 4.5-1. It includes the following recommended design features:

- Quick lime storage above the feeder.
- A slaker discharging directly into the stabilization tank.
- A single baffled tank to accomplish stabilization and storage.

Each of these recommended features will be discussed in depth in subsequent subsections.

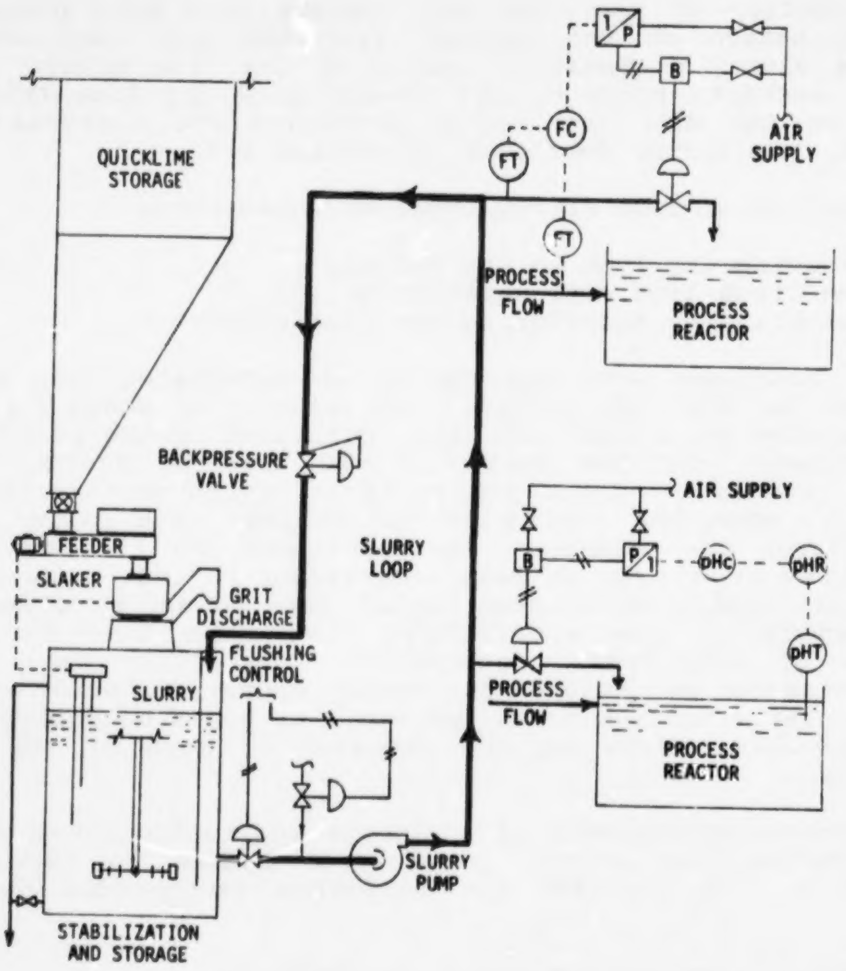

I/P
B
AIR SUPPLY
FC
FT
FT
QUICKLIME STORAGE
PROCESS FLOW
PROCESS REACTOR
BACKPRESSURE VALVE
SLURRY LOOP
AIR SUPPLY
B
P/I
pHC
pHR
pHT
FEEDER
SLAKER
GRIT DISCHARGE
FLUSHING CONTROL
SLURRY
PROCESS FLOW
PROCESS REACTOR
SLURRY PUMP
STABILIZATION AND STORAGE

Figure 4.5-1. Lime slurry system--schematic flow.

Source: Beals, J.L., Handling hydrated lime slurries.
Wallace & Tiernan, April 1976.

4.5.2 Dry Lime Feeding

4.5.2.1 Introduction--

The first step in slurry preparation is to deliver dry lime from a bin at a constant rate. Most lime scrubbing FGD systems use dry feeders for this purpose.

Dry feeders are not manufactured specifically for the feeding of lime; they are used in other industries for a wide variety of granular and powdered solids. Several suppliers manufacture dry feeders of varying specifications and cost. Generally, models suitable for preparation of lime slurry have an accuracy of between 1 and 5 percent by weight.

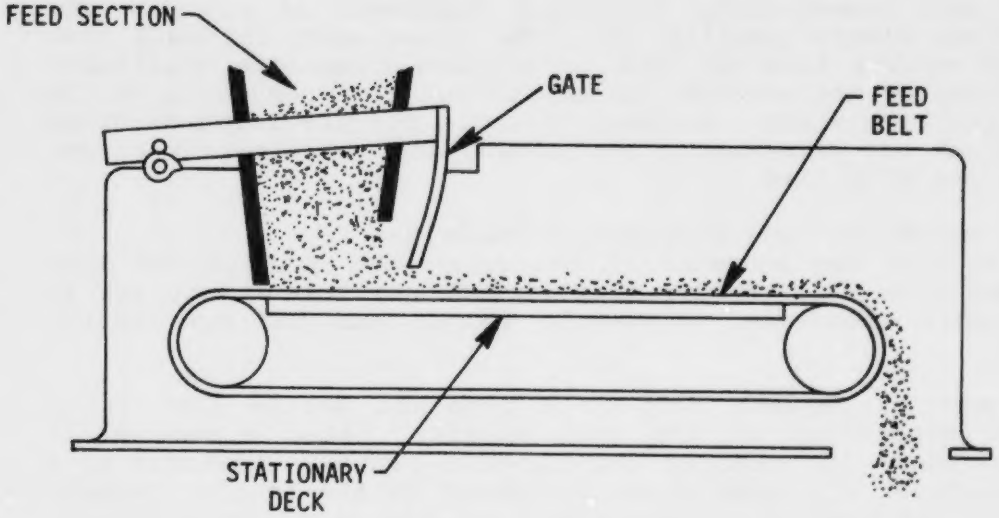
Not all commercially available equipment is suitable for use in lime slurry preparation. The types used for bulk conveying of solids such as coal or crushed stone are unsuitable because they do not provide the consistent flow needed to ensure uniform slurry quality. Feeders suitable for precision-blending applications are unnecessarily accurate and inordinately expensive for use with lime.

4.5.2.2 Volumetric and Gravimetric Feeders--

There are two methods of measuring the quantity of lime discharged from a dry feeder that provide sufficient accuracy at a reasonable cost--the volumetric method and the gravimetric method.

Volumetric feeders deliver a constant volume (ft^3/h) of material, regardless of its bulk density. When a volumetric feeder is used, the feeding mechanism is manually adjusted to a fixed position. If lime flows uniformly to the feeding mechanism and if the lime is of consistent quality (e.g., size distribution), a consistent weight of lime will be discharged within a measured accuracy of approximately 5 percent. Examples of both volumetric belt-type feeders, whose belt speed and the position of the feed regulating gate determine the volume of material fed, and vibrating volumetric feeders, in which electromagnetic vibration delivers a steady lime feed, are shown in Figures 4.5-2 and 4.5-3, respectively. Other types of volumetric feeder are also available. Volumetric feeders require continual supervision because any blockages that develop in the feeder throat or in the lower section of the feed bin will not clear automatically. Volumetric feeders usually require a smaller capital investment than gravimetric feeders.

Gravimetric feeders deliver a constant weight (lb/h) of material, thus compensating for variation in the lime quality as well as voids in the stream of solids. They are accurate to approximately 3 percent by weight. This improvement over the



FEED SECTION
GATE
FEED BELT
STATIONARY DECK

Figure 4.5-2. Volumetric belt-type feeder.

Source: Wallace & Tiernan Division, Pennwalt Corp.

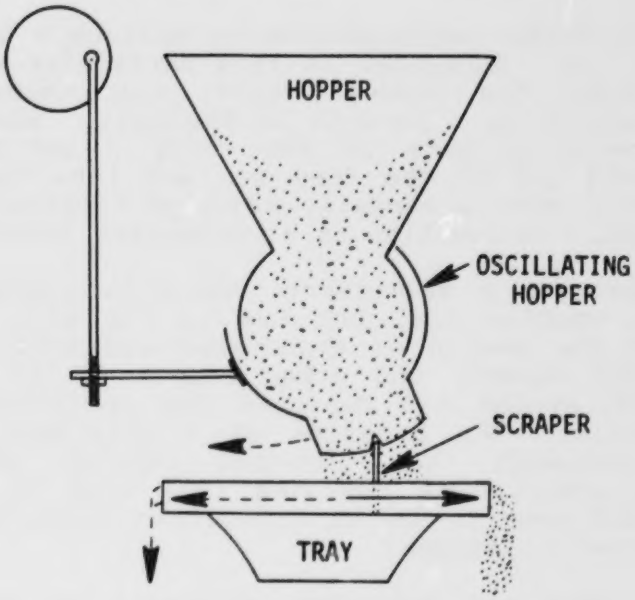

HOPPER
OSCILLATING HOPPER
SCRAPER
TRAY

Figure 4.5-3. Oscillating hopper volumetric feeder.

Source: Wallace & Tiernan Division, Pennwalt Corp.

specification of volumetric feeders is not significant and should not be a criterion for selection of a gravimetric type feeder over a volumetric type. However, gravimetric feeders are more reliable since their feeding mechanism is adjusted automatically by instrumentation operating in conjunction with a monitor that measures the weight of lime being fed. Thus, when a blockage begins to form in a gravimetric feeder the internal control system adjusts the feeding mechanism in such a manner as to increase the flow. This action in itself minimizes the occurrence of major blockages. If one should develop, the internal control of a gravimetric feeder would detect the low feed rate and sound an alarm. Thus the need for continual operator attention is reduced.

A gravimetric feeder manufactured by Wallace & Tiernan is shown in Figure 4.5-4. Contained in this particular machine is a weighdeck, beneath the conveyor belt, which measures the weight of lime carried on a section of the belt. Instrumentation adjusts a vertical gate so that only a set weight of material is allowed out of the feed bin and into the slaker. This same equipment, with a manually adjusted vertical gate and without a weighdeck, can function as a volumetric feeder.

The choice between a gravimetric and a volumetric feeder is, of course, a complex one, but one of the more important considerations is the design of associated equipment. If the lime feed bin, the slaker, and other components of the lime slurry preparation system are designed for operation without continual supervision, the benefits of a gravimetric feeder would probably outweigh the increased capital investment. However, when an operator is employed full time on a slurry system, there would seem to be no significant advantages from the use of a gravimetric feeder.

Although salesmen may encourage engineers to specify the feeder and slaker as a single item, the price often is significantly lower if they are bought separately. There are no technical reasons why the separate components should come from the same manufacturer as a single package.

4.5.2.3 Available Equipment--

Although many different feeding mechanisms are available in both gravimetric and volumetric feeders, only four have proved successful for handling lime:

1. The belt conveyor with a mechanical gate to regulate loading.

2. An oscillating hopper, which has a reciprocating mechanism that pushes ribbon-like layers of material from a fixed tray.

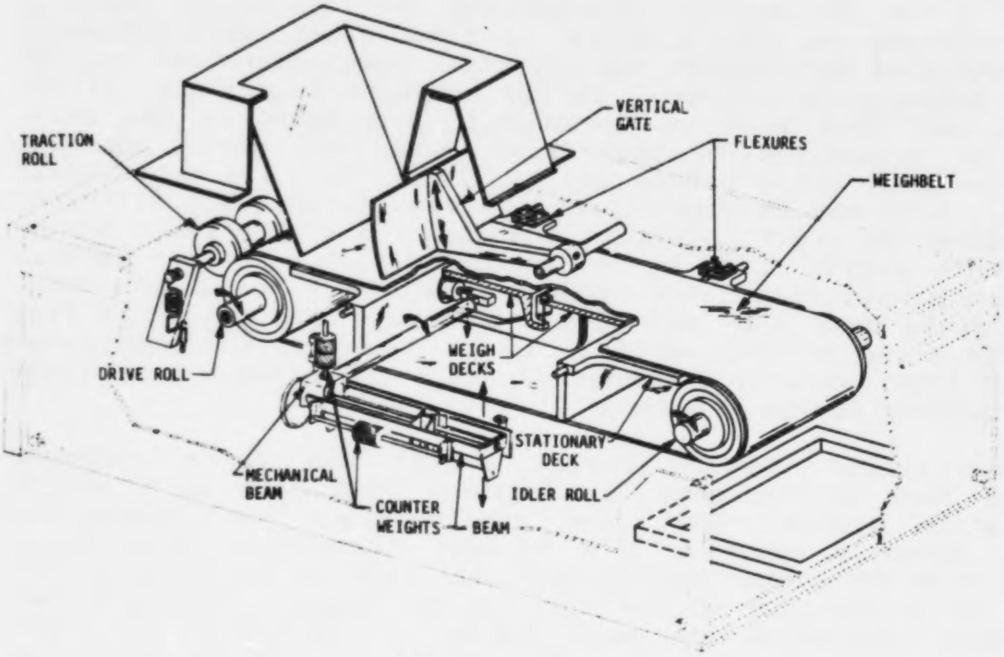

TRACTION ROLL
VERTICAL GATE
FLEXURES
WEIGHBELT
DRIVE ROLL
WEIGH DECKS
STATIONARY DECK
MECHANICAL BEAM
IDLER ROLL
COUNTER WEIGHTS
BEAM

Figure 4.5-4. Mechanical gravimetric feeder.

Source: Wallace & Tiernan Division, Pennwalt Corp.

3. A screw conveyor, which incorporates a rotating helix to move the material.

4. A vibrating device, in which the vibrations are induced either electromagnetically or mechanically.

An example of the belt-type feed mechanism is shown in Figure 4.5-4. This type of equipment is available from most of the larger manufacturers of intermediate-accuracy feeders, including Acrison, B-I-F, Merrick, Wallace & Tiernan, and Weightometer. The belt-type feeder is used most often in large lime slurry preparation installations. Most companies make several versions of this type of feeder, but the vertical-gate model shown in Figure 4.5-4 is usually recommended for quicklime service. Other versions use rotary gates, or fixed gates, with automatically-adjusted belt speeds and may offer some advantages in lime slurry preparation systems. In the conveyor feeder unit illustrated, the feed rate is dictated by the speed of the belt, which is determined by the drive motor and motor gearing. Variable-speed drive motors are available, but are not usually needed. Some manufacturers make the same feeder with different belt widths in order to expand the use of a single basic design and create a wide range of feeding capacities. Feeders of this type can handle feed rates ranging from 1 lb/h to 200,000 lb/h. For a given belt size and speed, however, turndown ratio from the gate alone is only about 10 to 1. Changing the feed range usually requires only a change of gears and occasionally minor modifications to the weighdeck.

Oscillating hopper (Figure 4.5-2) and screw conveyor feeders have an inherent disadvantage when used in a slurry preparation system. The usual configuration would place the feeder directly above a lime slaker; therefore, water vapor rising from the slaker could react with lime at the mouth of the screw or on the tray of the oscillating hopper. During normal continuous operation, the small amount of reaction is not especially troublesome, but when the feeder is stopped, the lime exposed to moist air reacts to form hard deposits, which could interfere with the operation of moving parts. During intermittent operation, these feeders require frequent cleaning and maintenance. Therefore, screw conveyor and oscillating hopper feeders are built primarily as small- or medium-capacity units, best suited for use in plants where the flow of lime is not intermittently stopped and restarted. B-I-F, Acrison, and Wallace & Tiernan manufacture screw-conveyor-type feeders. Oscillating hopper units are constructed primarily by foreign manufacturers.

Figure 4.5-5 shows a gravimetric feeder made by B-I-F, with a vibratory feed mechanism and a weigh belt. The intensity of vibration is regulated by a "control wedge" of hard rubber suspended from a scale beam. If the amount of lime on the weigh belt is less than specified, the control wedge drops, transmitting more vibrations to the feed plate. Several companies make vibratory feeders in both volumetric and gravimetric versions. Syntron Division of the FMC Corporation is a major manufacturer of volumetric vibratory feeders. Low initial cost is the principal advantage of this mechanism. Its main disadvantage is noise that, in large units, may reach a level that requires special sound proofing.

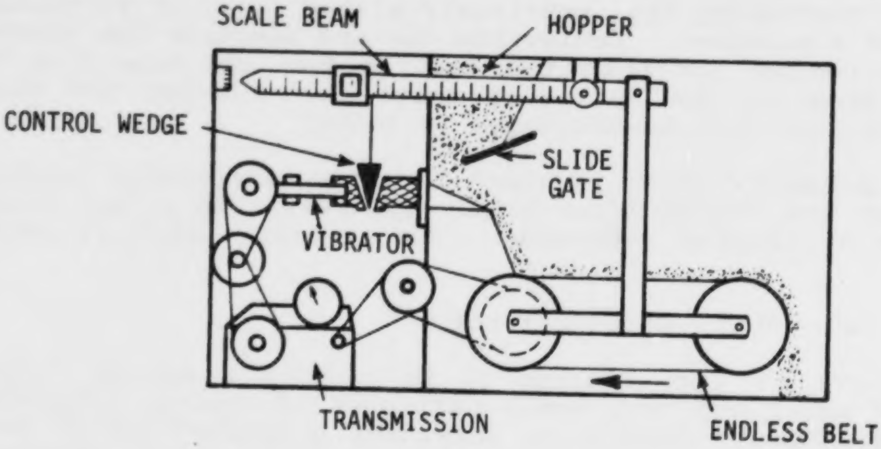


Figure 4.5-5. Gravimetric feeder.

Source: B-I-F, a unit of General Signal Corp.

4.5.2.4 Existing Facilities--

Of the 10 plants operating lime FGD systems during early 1978, six feed dry quicklime into slurry preparation systems and two buy hydrated lime as a byproduct from local chemical plants. These two plants, Paddy's Run and Cane Run, do not have slurry preparation systems of the type described here. No data are available on two other plants, Hawthorne No. 3 and Hawthorne No. 4.

The Phillips, Elrama, and both Bruce Mansfield plants use belt-type gravimetric feeders. In all these units, each feeder is so arranged that it can feed only one slaker. Phillips and Elrama both have five feeders, one of which is a spare. At Bruce Mansfield, four Merrick feeders are in use, each of which is capable of feeding quicklime at 50,000 lb/h and is actually operated to feed about 48,000 lb/h. There are no spare feeders.

Conesville uses five screw conveyors, each delivering about 8000 lb/h into individual slakers. Green River employs one conveyor screw to deliver about 8000 lb/h into either of two slaking tanks.[1] Neither the Conesville nor Green River system provides for variation in the rate of lime feed to the slaker. The systems are designed for a specific and constant feed rate.

All of these systems are operated intermittently. At Phillips and Elrama, switching on and off is done manually. At Green River and Conesville, semiautomatic controls are used, and similar controls are being installed at Bruce Mansfield.

4.5.3 Lime Slurrying (Slaking)

4.5.3.1 Introduction--

Lime slurry may be obtained by three processes: slaking quicklime, purchasing dry, previously slaked lime, or purchasing slurry from a producer. Louisville Gas and Electric has elected the third option for both the Paddy's Run and Cane Run FGD systems. Most of the operating units have elected the first option, and this will be discussed in detail.

When quicklime (CaO) is added to water, a vigorous reaction occurs with the evolution of heat. The result is a lime slurry suspension of calcium hydroxide. The process itself is called slaking.

$$CaO + H_2O \rightarrow Ca(OH)_2 + heat$$

The objective of lime slaking is to produce a smooth, creamy mixture of water and very small particles of calcium hydroxide. This mixture should contain no unreacted quicklime and no large calcium hydroxide crystals. A lime slaker mixes regulated streams of quicklime and water under the appropriate agitation and temperature conditions to disperse soft hydrated particles as they form. Dispersion must be rapid enough to prevent localized overheating and rapid crystal growth of the hydroxide; however, the mixture must be held in the slaker long enough to permit complete reaction.

4.5.3.2 Service Description--

Quicklime of any type or size distribution can be processed in a properly designed slaker. The speed at which various grades and sizes of quicklime can be slaked varies considerably and directly influences the rate at which a slaker can produce lime slurry. A highly porous lime slakes more rapidly than a "hard-burned," nonporous material. Finely divided particles slake more rapidly than large lumps, and high-calcium limes slake more rapidly than magnesian limes. The American Society for Testing and Materials (ASTM) has developed testing methods to determine the relative slaking rates of quicklimes. It is not possible to predict the rate at which a slaker can produce a good slurry unless the lime has been tested by standard methods such as ASTM C25-72 and ASTM C110-716. The rated capacities of commercial slakers are based on lime that slakes rapidly. Actual slurry production rates are often lower, especially when slaking pebble lime with high magnesium content.

Because no technology has been developed that will automatically produce slurry of optimum characteristics, operation of a slaker is often described as an "art." The operator must manipulate certain variables, depending upon the characteristics of the slaker. At present, two types of slaker are available: detention slakers and paste slakers. With a "detention" slaker the temperature of the mixture is monitored in order to establish a range of about 50°F over which the slaker produces slurry of adequate quality. The temperature may be controlled by varying the amount of water added.

With a "paste" slaker, the torque of the mixer shaft is monitored as a guide to optimum conditions, since measuring the temperature of a thick paste is difficult. Detention and paste slakers, the types used most commonly with FGD systems, are described under Available Equipment, Section 4.5.3.3.

The range of slaking conditions is limited in any type of slaker by the occurrence of "drowning" or "burning," conditions that produce low-quality slurry. "Drowning" is caused by the presence of too much water in proportion to lime and is indicated by a sharp drop in slaking temperature when the flow of water is increased slightly. The result is that the calcium hydroxide being produced adheres to the quicklime particles. Each quicklime particle is surrounded by a layer of relatively impervious and unreactive calcium hydroxide. At the other extreme, "burning" also produces particles of unreacted quicklime surrounded by a hard impervious layer of hydrate. In burning, insufficient water causes localized overheating at the surface of the quicklime particles. The very high temperatures that develop cause formation of unreactive oxide and hydrate crystals. Burning usually produces steam, which removes water from the mixture and causes a further increase in temperature. Burning is therefore indicated by a rapid rise in slaking temperature when flow of slaking water is decreased slightly. If not controlled, it will cause serious overheating that may damage the equipment.

A lime slaker must include provisions for removing grit from the slurry. Grit consists of sand and similar impurities, plus the carbonate cores of quicklime pebbles that were not calcined during lime manufacture. Good-quality quicklime contains 1 to 2 percent grit; poor grades may contain up to 5 percent. The grit is usually discarded in a sludge pond or landfill. Grit particles that remain in the slurry cause abrasive damage to slurry handling equipment. Properly slaked slurry of pure hydrated lime can be considered nonabrasive, since the lime particles are soft, lightweight solids that cannot scratch or erode metals.

4.5.3.3 Available Equipment--

Equipment used for lime slaking in a scrubbing system should be specifically designed for this service.

A detention slaker is shown in Figure 4.5-6. Quicklime and water are fed to the slaker in specific proportions in order to produce a slurry containing 20 to 30 percent solids. The mixture is agitated with a high-speed propeller mixer. From the agitated chamber, slurry flows into a quiet section where grit settles out. Degritted slurry is then diluted with additional water and flows to a stabilization tank. Grit is continuously removed from the quiet section by means of a mechanical scraper. It is rinsed with a small stream of water and discarded. In a detention slaker, water is added to each chamber; the amount of water is manually proportioned by trial and error to achieve the best results with the lime being used. Slurry usually is retained in a detention slaker 20 to 30 minutes at a temperature of about 167°F.

The paste slaker operates on the pug mill principle, kneading a thick mixture of lime and water. Feeds are proportioned to produce a putty-like mixture containing about 40 to 50 percent solids. The mixture is blended in a narrow trough by paddles that rotate on horizontal shafts. The thick slurry continuously overflows the end of the trough into a dilution chamber, where more water is added and grit is separated, rinsed, and discarded. A typical paste slaker is shown in Figure 4.5-7. Slurry is retained in a paste slaker for only 5 to 10 min. The slaking temperature is usually about 185° to 194°F.

Neither the detention slaker nor the paste slaker has proved superior for all applications. Both types have their proponents and both offer certain advantages. Characteristics of these slakers are listed in Table 4.5-1. In general, the detention slaker is a more flexible unit that can be tailored to match exactly the requirements of a specific installation. It is simple in design, but bulky. The paste slaker is more complex mechanically. It is much smaller and only available in certain sizes. The freshwater requirements of the two slakers are markedly different, and this is discussed in Section 4.5.4.4.

Both high temperature and long retention time are required to slake some poor-quality grades of quicklime. It is uneconomical to slake poor-quality quicklime with paste slakers if it is necessary to operate several slakers at reduced capacity in order to provide adequate retention time. In a detention slaker, poor-quality quicklime can be processed by heating the feed water, thereby providing both high temperature and longer retention time. Preheated water can also be used with a paste slaker, but the technique is less effective since the lower water-to-lime ratio limits the amount of preheat that can be used without causing "burning."

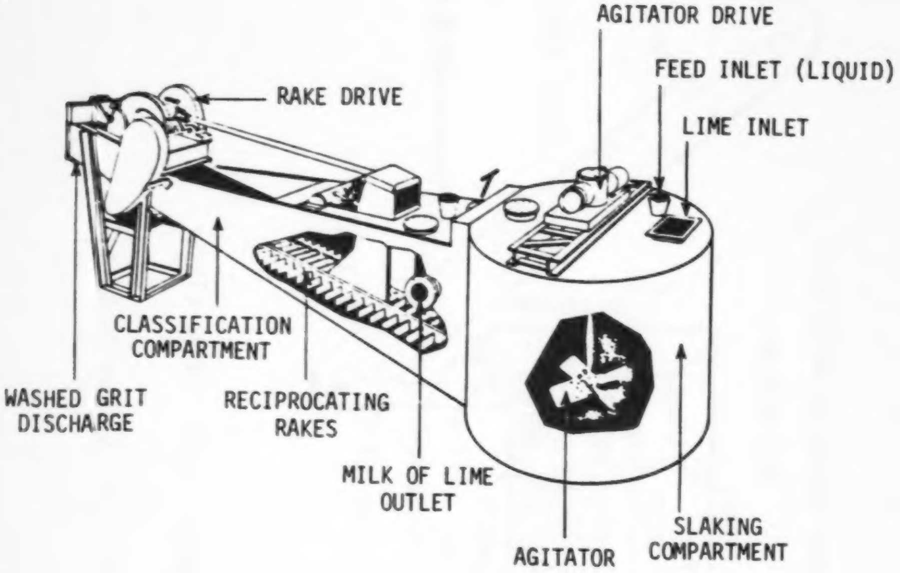

AGITATOR DRIVE
FEED INLET (LIQUID)
RAKE DRIVE
LIME INLET
CLASSIFICATION COMPARTMENT
WASHED GRIT DISCHARGE
RECIPROCATING RAKES
MILK OF LIME OUTLET
AGITATOR
SLAKING COMPARTMENT

Figure 4.5-6. Detention slaker.

Source: Dorr-Oliver Corp.

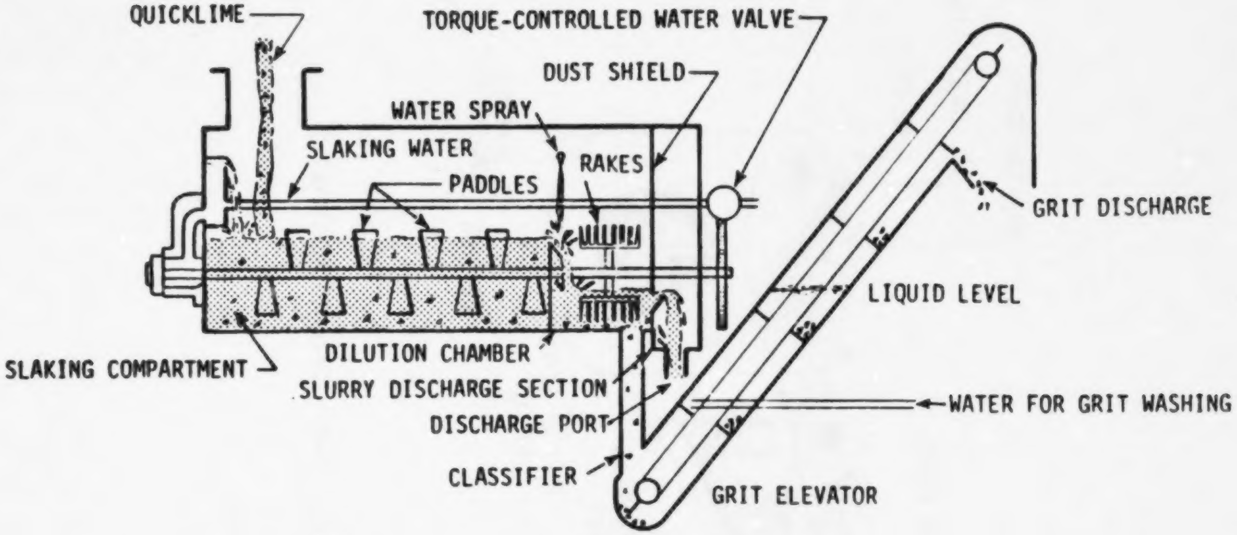

QUICKLIME
TORQUE-CONTROLLED WATER VALVE
DUST SHIELD
WATER SPRAY
SLAKING WATER
RAKES
PADDLES
GRIT DISCHARGE
LIQUID LEVEL
SLAKING COMPARTMENT
DILUTION CHAMBER
SLURRY DISCHARGE SECTION
WATER FOR GRIT WASHING
DISCHARGE PORT
CLASSIFIER
GRIT ELEVATOR

Figure 4.5-7. Paste slaker.

Source: Wallace & Tiernan Division, Pennwalt, Corp.

Table 4.5-1. CHARACTERISTICS OF DETENTION AND PASTE SLAKERS

	Detention slaker	Paste slaker
Size of equipment for equal capacity	Large equipment	Smaller equipment
Size of available equipment	Can be built in any size	Available only in standard sizes, with capacities limited to about 8000 lb quicklime/h
Quality of quicklime	High-quality or poor-quality quicklime	High-quality quicklime
Lime size range	Can handle any size up to 2-in. lumps	Should be limited to particles smaller than 3/4 in.
Mechanical complexity	Very simple	Moderately complex
Water-to-lime ratio	Needs more slaking water	Needs less slaking water
Ventilation requirements	Natural draft ventilation may be sufficient	Needs a powered ventilation system
Safety controls	Should have high-temperature alarm. Low-temperature alarm is advisable	Should have high torque alarm and a safety shutdown system. Needs torque controls to regulate addition of water
Slurry quality	Larger particles	Usually slightly smaller particles
Initial cost	Less costly	More costly

Slakers must be ventilated to prevent condensation of vapor inside the dry feeder. If it is not allowed to escape, the vapor condenses and reacts with lime dust to form hard deposits on the slaker surface. A slaker ventilation system must remove the hot, humid air. However, it should also be designed to prevent discharge of lime dust into the atmosphere.

As the slaking temperature increases, the amount of moisture evaporating from the slaking mixture increases; therefore, paste slakers generally create more problems from condensation than do detention units. Smaller detention slakers are simply vented into the immediate area via a small scrubbing column, through which a portion of the cool slaking water is admitted. Only a very small draft of air is needed; natural draft is often sufficient to protect the feeder. Less moisture is released in the work area; however, if a small stream of compressed air is used to discharge the humidified air through plastic ductwork to the outside of the building, the feeder area should be protected from the moisture.

Because they produce greater amounts of moisture, paste slakers usually require some type of forced ventilation. Wallace & Tiernan supplies a water-operated eductor that uses a portion of the dilution water to exhaust a small amount of air from the slaking chamber. The same device is used with some brands of detention slakers.

Most ventilation systems supplied with commercial slakers are poorly suited for installations where the slaker is operated intermittently. When the slaker is shut down and flow of water is stopped, ventilation systems that use water eductors also stop functioning, even though water continues to evaporate from the slaking mixture. Condensation within the feeder usually occurs on each shutdown. With a belt-type feeder, this condition is usually tolerable. With vibrating feeders, screw conveyors, or oscillating hoppers, however, condensation can cause maintenance difficulties.

Although lime slurries are most often prepared by detention and paste slakers, other methods of reacting water with quicklime are available. One method is "hydration," or "dry hydration," the system used by lime manufacturers to produce commercial hydrated lime. Hydration units are small chemical plants that react lime with steam in closed vessels and remove the hydrated product by air classification. The resulting powder is mixed with water to form a slurry. Dry hydration is most economical if the heat of the reaction can be profitably recovered. In many installations, the heat of reaction is used to preheat air for feeding to a lime kiln. This process has been proposed for use in large lime scrubbing FGD system because it allows preparation of the slurry with recycled water, which cannot be used directly in conventional lime slaking.

Another potential lime slurry preparation system is the "ball mill slaker," which wet grinds the quicklime. The resulting slurry consists of calcium hydroxide, grit, and scale compounds finely ground and suspended in water. The advantage of this process is that close chemical control is unnecessary. Any type of water can be used, the slaking temperature is unimportant, and even the poorest grades of lime can be treated. Any limestone that might be in the feed material is also present in the slurry and is available alkali in the FGD absorber. Disadvantages of the ball mill include high initial cost, very high operating costs, formation of an abrasive slurry, and operation so noisy that the equipment is usually housed in a separate building.

Some manufacturers offer general purpose mixing equipment as a substitute for a lime slaker. Simple tanks equipped with agitators have been used occasionally for slaking, on the assumption that it is merely a mixing process. With this equipment, quicklime and water are fed into the tank and the mixture is stirred briskly. Although a "batch slaker" of this type is a simple device, it invariably produces a poor quality slurry. Even with high-energy agitation, slaking may not be uniform. Hard, crystalline lime particles are formed, slaking is usually incomplete, and part of the lime is lost as a hard scale that forms in the tank. The slurry is usually very erosive and reacts slowly in the FGD absorber. This type of system is much larger than a continuous slaker and requires more operating and maintenance labor.

4.5.3.4 Water Requirements for Slaking--

When quicklime is slaked in either a detention or a paste slaker, the quality of the lime is affected by the slaking water used. Impurities, such as those found in recycled water from a lime scrubbing FGD system, reduce the slaking rate and cause the production of large, dense particles of partially hydrated lime. The slurry may be more abrasive and thereby increases the maintenance requirement for the FGD system. Slaking water should be free of high concentrations of ions such as carbonates, bicarbonates, sulfates, or phosphates that will precipitate in the presence of calcium and cause a scaling problem. Similarly, other metal ions that will precipitate in the presence of hydroxide ions are also objectionable. High concentrations of chlorides in slaking water do not appear to be detrimental to the slaking process; however, high concentrations of chlorides may increase the degree of equipment corrosion.

Opinions differ regarding the use of recycled scrubber water for slurry dilution. If the slaker is operated properly and if complete slaking of quicklime has been achieved, dilution with recycled water probably may be satisfactory, and only minimal use of freshwater would be recommended. A portion of the lime will react with the dissolved sulfates and sulfites in the recycled water, causing precipitates to form on a proportional amount of suspended lime.

The slaked lime is usually diluted to a concentration of 10 to 25 percent calcium hydroxide by weight. Dilution is required so that the slurry can be pumped successfully with centrifugal pumps and fed into scrubbing equipment through control valves.

4.5.3.5 Existing Facilities--

Table 4.5-2 presents data from six existing plants and the now-terminated experimental scrubber at the Four Corners Power Station. Updated information is presented in "EPA Utility FGD Survey" prepared bimonthly by PEDCo Environmental, Inc., for the U.S. Environmental Protection Agency (EPA Contract Number 68-01-4147, Task No. 3).

4.5.4 Slurry Stabilization and Storage

4.5.4.1 Introduction--

Slurry storage not only provides a surge volume between the slaker and the FGD process, but also allows time to "stabilize" the slurry. Addition of dilution water to a concentrated slurry causes a series of chemical reactions between the lime and the minerals dissolved in the water, such as alkaline-earth salts, chlorides, sulfates, phosphates, etc. The reactions, which are normally completed in less than 15 minutes in a slurry preparation system, cause the formation of hard, insoluble, crystalline materials. The primary function of slurry storage is to hold freshly diluted slurry until these scale-forming reactions are complete. The slurry is then said to be stabilized. If no more water is added, and if the slurry does not absorb carbon dioxide from the air, no further scale formation reactions will occur. Maintenance expenses therefore can be greatly reduced by allowing sufficient stabilizing time for the slurry before it passes through pumps, small-diameter piping, and/or control valves.

4.5.4.2 Service Description--

A critical design point in a slaker installation is the conveying of diluted slurry to the stabilization tank. Since crystalline scale compounds are formed most rapidly during the first minute after slurry dilution, slurry should be transferred to the stabilization tank by the fastest possible method. Ideally, the slaker would be located directly above the stabilization tank and the slurry would simply drop through a large chute into the tank. If horizontal movement of the slurry is required, open troughs that are easily removable for cleaning are preferable to piping. In no case should slurry be pumped directly from a slaker into a storage tank, since pump failures and plugging of the pipes could be excessive.

In a well-designed system, a large stabilization tank is used so that most of the scale compounds are present as a suspension. As further scale compounds are formed, they adhere to the suspended crystals, which increase in size and eventually settle to the bottom of the tank as a loosely compacted sludge.

Table 4.5-2. OPERATING CHARACTERISTICS OF LIME SLAKING FACILITIES[1,2,5,6,7]

Plant Name	Bruce Mansfield	Four Corners	Phillips	Elrama	Conesville	Green River
Unit capacity, MW	835	160	410	510	400	64
Slaker type	Detention	Detention	Paste	Paste	Paste	Mix tanks
Quicklime type[a]	Thiosorbic	High calcium	High-calcium[b] dolomite	Thiosorbic	Thiosorbic	High calcium
Quicklime size, in. (top size)	1-3/4	3/8	1/2	1-1/2	1-3/4	3/4
Number of feeders	4	1	4	4	5	1
Number of slakers	4	1	4	4	5	2
Feeder type	Gravimetric	Not reported	Gravimetric	Gravimetric	Screw conveyor	Screw conveyor
Normal lime rate each feeder, lb/h	48,000	Not reported	8000	8000	8000	4000
Water used for slaking	Fresh	Fresh	Fresh	Fresh	Fresh	Fresh
Slaking temperature, °C (°F)	93 (199)	82 (180)	60 (140)	60 (140)	74 (165)	55 (131)
Slaker alarms	No	Yes	Yes	Yes	No	No
Slaker shutdown controls	No	No	Yes	Yes	No	No
Water used for dilution	Recycled	Fresh	Fresh	Fresh	Recycled	Fresh
Final slurry concentration, % solids	10	25	14	14	Approx. 15	20-25
Grit removal	Yes	Yes	Yes	Yes	Yes	Yes

[a] Refer to Section 4.4.1 for definitions of quicklime types.

[b] High-calcium lime used; various dolomitic limes experimented with to prevent scaling.

In a small tank, there would be proportionately fewer suspended crystals and a larger proportion of the scale-forming compounds would attach to crystals adhering to the walls of the tank, thus increasing the formation of a hard scale.

Figure 4.5-8 depicts a typical stabilization tank with a baffle installed to prevent short-circuiting of diluted slurry to the FGD system. A dilution tank with two chambers or two separate, staged tanks may improve the quality of the slurry fed to the FGD absorber. In such a slurry handling system, the first tank would be very large. Slurry from this tank might flow by gravity into a second tank. Fully stabilized slurry would then be pumped from the second tank to the scrubber system.

Solids tend to accumulate in the corners of square tanks or along the perimeter in the bottom of flat-bottomed circular tanks, and they may become compacted into a concrete-like mass. Such deposits usually are left in place when the tanks are cleaned. If agitation is efficient, however, reduction in the useful volume of the tanks as a result of these deposits is not likely to exceed 2 to 5 percent.

Lime slurry tanks should be covered to prevent excessive absorption of ambient carbon dioxide, which increases scale potential by the formation of calcium carbonate. If transfer tanks are used, it is best to connect them and the storage tanks with vent piping in order to minimize the amount of fresh atmospheric air drawn into the system during slurry transfer. A slurry stabilization and storage tank should be fitted with vent piping if the air near the tank is likely to contain more than normal atmospheric quantities of carbon dioxide.

Although proper design will reduce the frequency of cleaning, stabilization and storage tanks must be shut down and emptied periodically so that deposits can be removed. Installation of side-entering manholes will simplify this procedure. Proper design of the stabilization and storage tank system avoids the need for redundant slakers and lime feeders, thereby decreasing initial costs and simplifying operation. Providing duplicate stabilization tanks permits easy maintenance. When both tanks are filled with slurry, the slaker may be shut down and cleaned without interrupting scrubber operation. If any part of the equipment is to be duplicated, it should be the stabilization tank system. Slakers and feeders usually can be repaired quickly, provided spare parts are stocked. Care should be taken in the design of a lime system to allow for a large inventory of finished slurry so that scrubber operation can continue while the feeding and slaking equipment is down for maintenance.

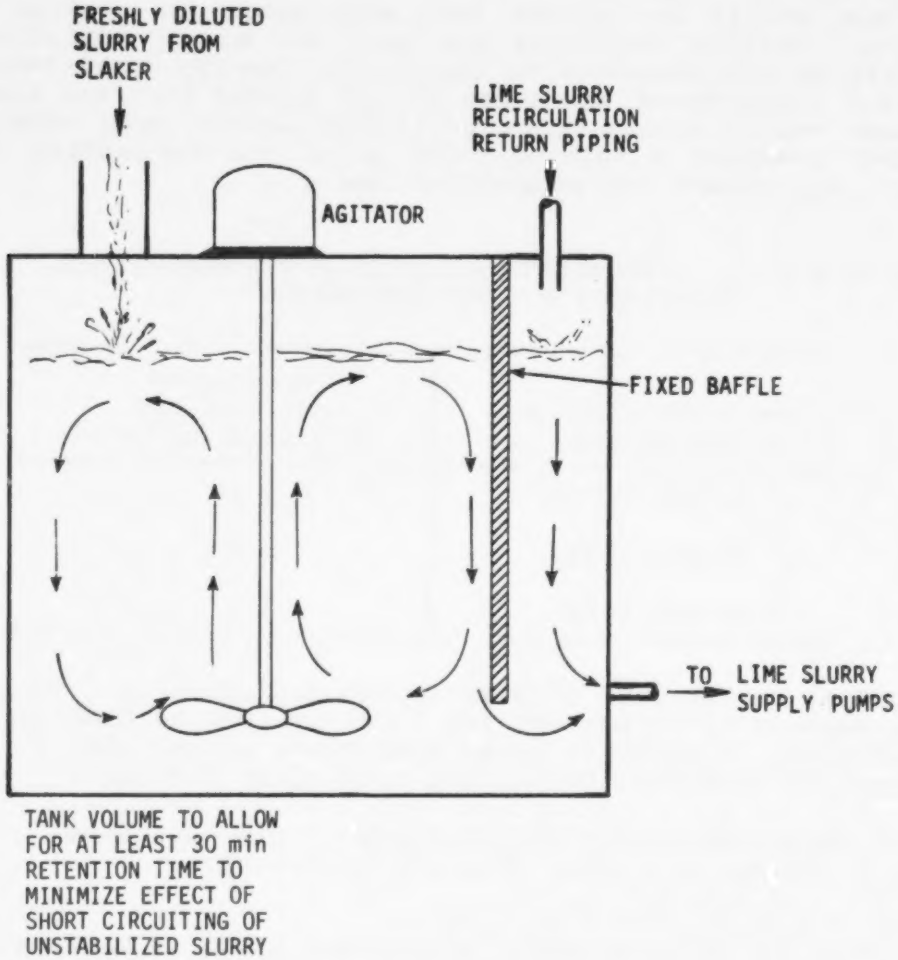

FRESHLY DILUTED
SLURRY FROM
SLAKER
LIME SLURRY
RECIRCULATION
RETURN PIPING
AGITATOR
FIXED BAFFLE
TO LIME SLURRY
SUPPLY PUMPS
TANK VOLUME TO ALLOW
FOR AT LEAST 30 min
RETENTION TIME TO
MINIMIZE EFFECT OF
SHORT CIRCUITING OF
UNSTABILIZED SLURRY

Figure 4.5-8. Typical stabilization tank (simplified).

Stabilization tanks are often constructed from carbon steel and in some cases from fiberglass reinforced plastic.[2] The tanks should be about as deep as they are wide since shallower tanks require more energy to achieve thorough agitation. Except for use in tanks with capacities of less than 1000 gal, agitators should be vertical-shaft, top-mounted units located axially within the vessel. Agitators with internal bearings should not be used, nor should any system that uses water for sealing or lubrication. Turbine impellers are best for slurry agitation, usually with motors connected to the shafts through speed-reduction gears.[3] High-speed agitation is not needed for lime slurry, because well-prepared lime particles settle very slowly. Table 4.5-3 provides a rule-of-thumb guide for estimating the horsepower requirement for an agitator motor.

Table 4.5-3. APPROXIMATE AGITATOR MOTOR HORSEPOWER REQUIRED FOR LIME SUSPENSION[a]

Lime slurry solids concentration	Horsepower per 1000 gal of slurry agitated
1 lb/gal (17%)	0.25
2 lb/gal (34%)	0.50
3 lb/gal (51%)	1.0

[a] Applies to tanks of 3000 to 15,000 gal capacity. Increase horsepower by 50 percent for tanks of 1000 to 2500 gal capacity. Applies to tanks with depth approximately equal to diameter, containing four fixed baffles.

Modified from Preparation and Handling of Lime Slurries, Wallace & Tiernan Division, Pennwalt Corporation.

The data on agitator motor horsepower given in Table 4.5-3 are too low for holding either particles of grit or large crystals of scale in suspension. The heavier particles will accumulate at the bottom of the tank and must be removed during periodic cleanings. Many engineers try to reduce the quantity of heavy, abrasive material that enters the circulation pump and passes through the control valve into the reaction tank. Others prefer to increase agitation to hold heavy particles in suspension. They are willing to accept an increase in the abrasiveness of the slurry in exchange for reducing the frequency of tank cleaning.

Power consumption and turbine speed must be greatly increased, perhaps doubled, if the tanks are not fitted with fixed baffles. As shown in Figure 4.5-9, baffles consist of two to four vertical plates, each about one-twelfth the diameter of the tank, mounted on a framework that supports the plates away from the sides and bottom of the tank at a distance of about one-half the baffle width. Baffles, which break up the circular motion of the slurry, should not be attached directly to the sides and bottom of the tank because solid deposits will form behind them, decreasing the effective volume of the tank and hampering slurry agitation. Three baffles in a tank generally are sufficient. More than four do not improve the agitation further.

A few operators further treat the lime slurry after stabilization by pumping stabilized slurry into a final storage tank through a classifier that separates heavier particles of grit and scale.

4.5.4.3 Existing Facilities--

Table 4.5-4 summarizes the data on stabilization and storage systems at operational lime FGD facilities. The available data indicate that some provision for stabilization and removal of heavier particles is included as part of the design in most installations. The experimental system that was operated at the Four Corners station of Arizona Public Service Company appears to have been the most advanced.[1,4] The slakers produced a lime slurry, which was discharged into a dilution tank, from which the heavier solids were later removed in a thickener. Clarified slurry was pumped to the scrubber while underflow was removed to a sludge disposal facility.

At Bruce Mansfield, (Figure 4.5-8) each of the three slakers delivers about 900 gal/min of 10 percent lime slurry into a 36-ft-diameter transfer tank, which provides almost an hour of retention time at the maximum slurry production rate.[5] The transfer tank is fitted with special underflow pumps to remove accumulated solids. Slurry is transferred intermittently from the transfer tank into a smaller recycle tank that allows less than 10 min retention. A schematic of this system is shown in Figure 4.5-10.

Data from the Conesville station are the most complete,[2] as shown in Figure 4.5-11. There the slurry from all slakers is discharged into a 15,900-gal tank, which provides about 30 minutes of retention time at maximum slurry production rate. Slurry at approximately 15 percent solids is pumped intermittently with a pump designed to deliver 660 gal/min into a large storage tank of 51,700-gal capacity. The slurry is then pumped as required to the scrubber with another set of pumps in a recycle loop designed to deliver up to 522 gal/min. Plant operators report a usage of 483 gal/min of slurry at 60 percent boiler load. Agitators are fitted with motors equivalent to about 3 hp/1000 gal of slurry. Actual operating horsepower has not been measured. The tanks have no baffles.

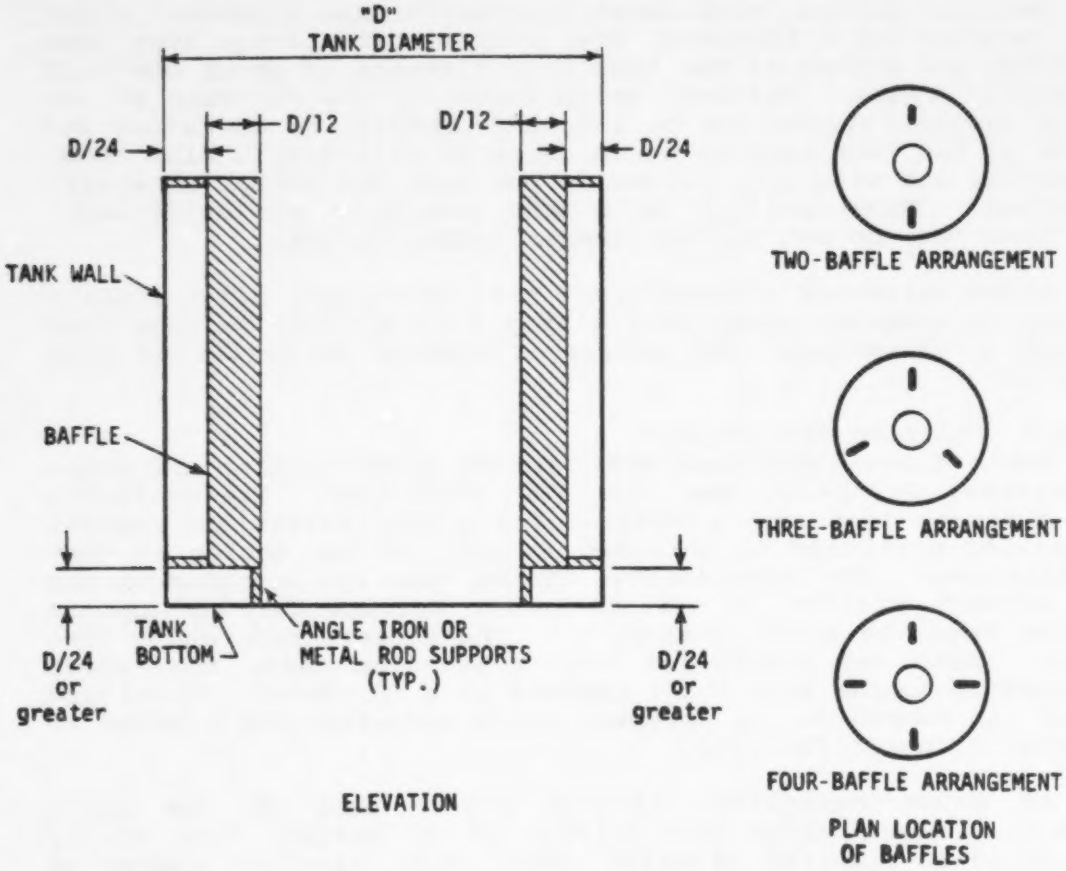

"D"
TANK DIAMETER
D/24
D/12
D/12
D/24
TANK WALL
BAFFLE
TANK BOTTOM
ANGLE IRON OR METAL ROD SUPPORTS (TYP.)
D/24 or greater
D/24 or greater
ELEVATION
TWO-BAFFLE ARRANGEMENT
THREE-BAFFLE ARRANGEMENT
FOUR-BAFFLE ARRANGEMENT
PLAN LOCATION OF BAFFLES

Figure 4.5-9. Agitator baffle design.

Table 4.5-4. STABILIZATION AND STORAGE SYSTEMS[1,2,5,6,7]

	Bruce Mansfield	Four Corners	Phillips	Elrama	Conesville	Green River
Slurry from slakers, maximum feed rate	2,700	20	397	297	517	61
Slurry composition, % solids	10	25	14	14	Approx. 15	20 to 25
Stabilization tank capacity, gallons	150,000	[a]	13,000	13,000	15,900	1980
Stabilization tank, agitator motor horsepower	[a]	[a]	7.5	7.5	5	5
Storage tank capacity, gal	8,500	[a]	NA	NA	51,700	NA
Storage tank, agitator motor horsepower	[a]	[a]	NA	NA	15	NA

[a] Data not reported.

NA - Not applicable.

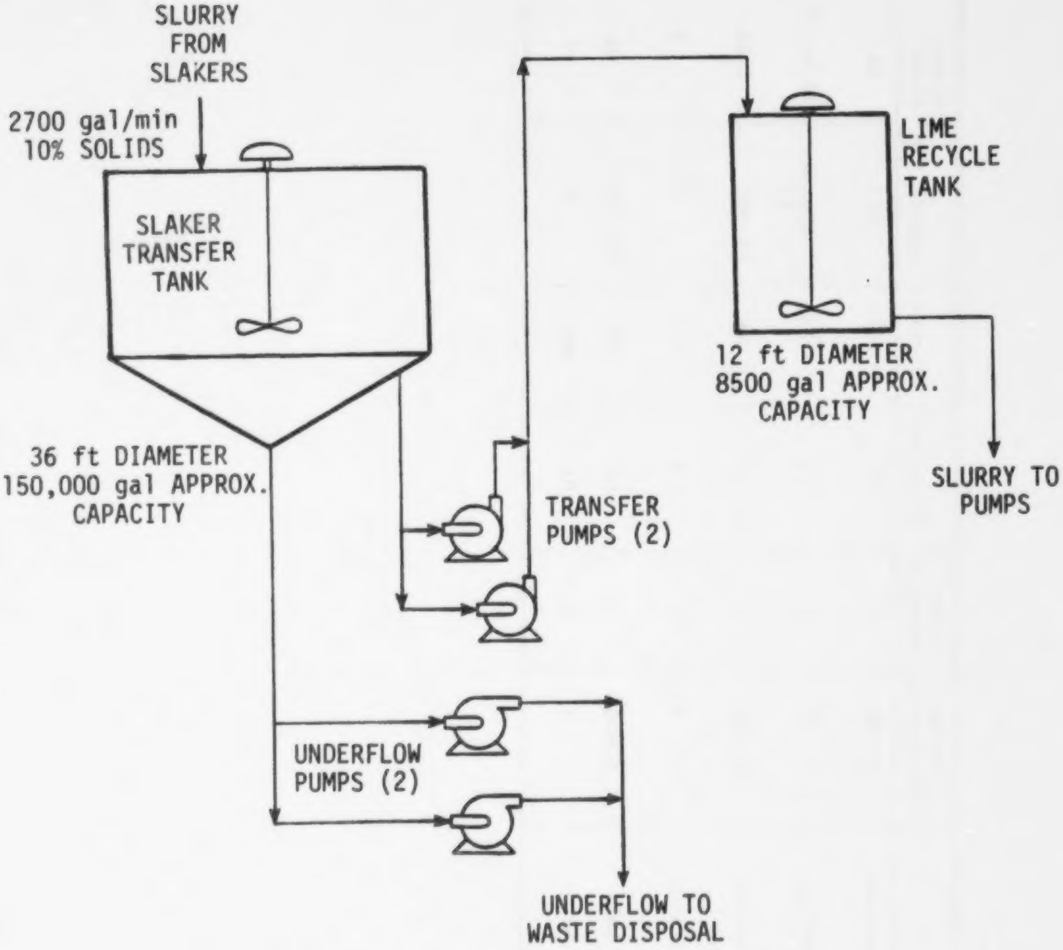

SLURRY FROM SLAKERS
2700 gal/min
10% SOLIDS
SLAKER TRANSFER TANK
36 ft DIAMETER
150,000 gal APPROX.
CAPACITY
TRANSFER PUMPS (2)
LIME RECYCLE TANK
12 ft DIAMETER
8500 gal APPROX.
CAPACITY
SLURRY TO PUMPS
UNDERFLOW PUMPS (2)
UNDERFLOW TO WASTE DISPOSAL

Figure 4.5-10. Bruce Mansfield stabilization and storage system.

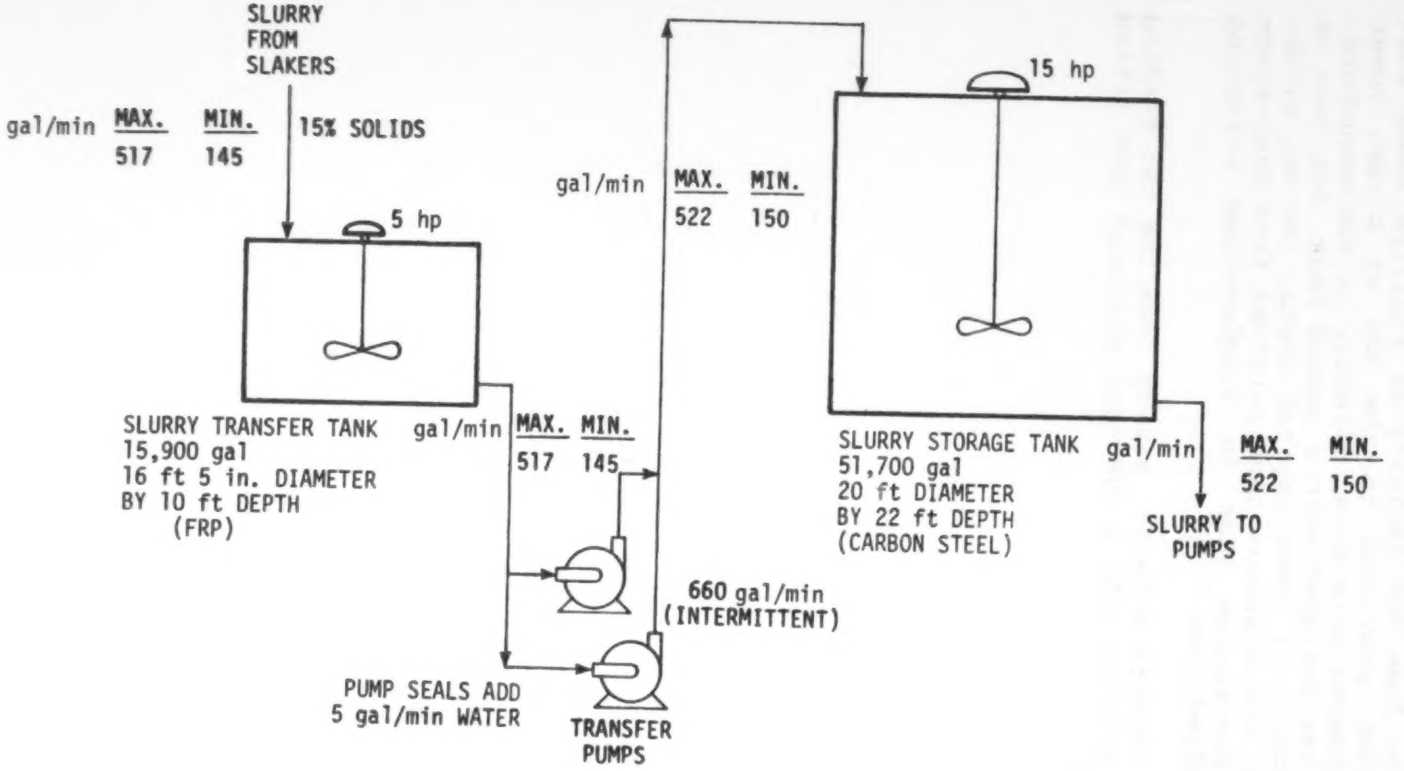

SLURRY
FROM
SLAKERS
gal/min MAX. 517 MIN. 145
15% SOLIDS
5 hp
SLURRY TRANSFER TANK
15,900 gal
16 ft 5 in. DIAMETER
BY 10 ft DEPTH
(FRP)
gal/min MAX. 517 MIN. 145
PUMP SEALS ADD
5 gal/min WATER
TRANSFER
PUMPS
660 gal/min
(INTERMITTENT)
gal/min MAX. 522 MIN. 150
15 hp
SLURRY STORAGE TANK
51,700 gal
20 ft DIAMETER
BY 22 ft DEPTH
(CARBON STEEL)
gal/min MAX. 522 MIN. 150
SLURRY TO
PUMPS

Figure 4.5-11. Conesville stabilization and storage system.

At Phillips and Elrama, all slakers discharge to a common tank. Figure 4.5-12 presents a diagram of the stabilization and storage system of the lime FGD facility at Phillips Power Station, which is almost identical to the one at Elrama Power Station. Slurry is pumped only once, directly to the scrubbers. The original system was designed with a second tank, but this is not now in use. Because of lower capital costs, the SO_2 scrubbing systems at both the stations have switched from dual-stage scrubbing using high-calcium lime to single-stage scrubbing using magnesium modified lime.[6,7]

At Green River (Figure 4.5-13), slurry from the two slaking tanks is dropped by gravity into a 1980-gal mix/hold tank fitted with a 5-hp agitator.[1]

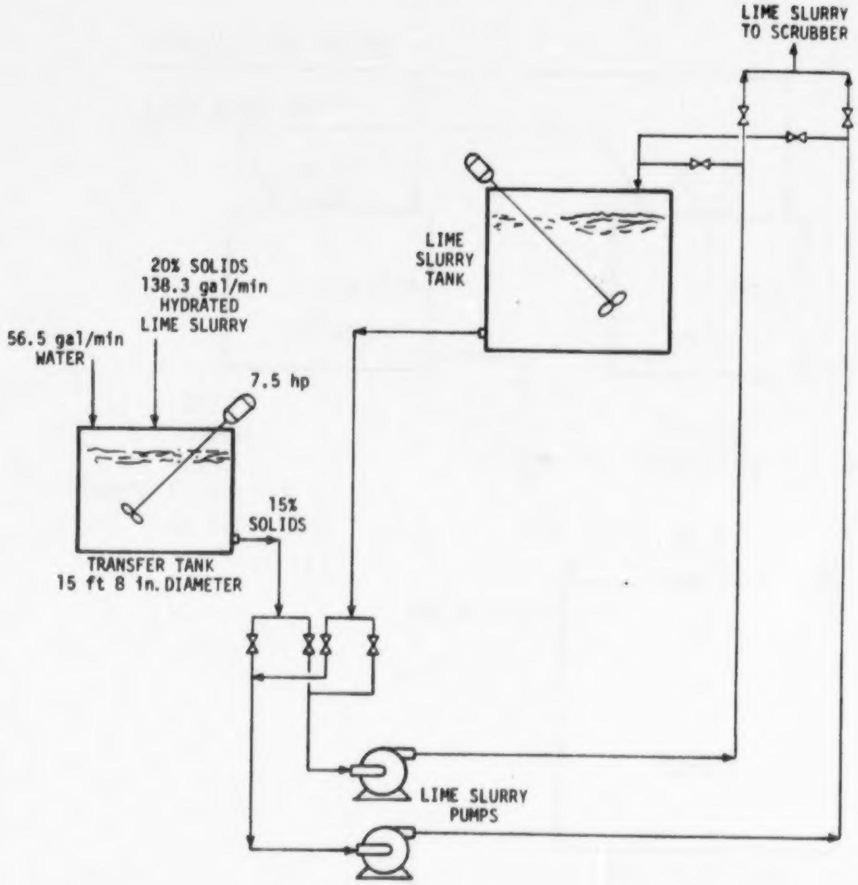

LIME SLURRY
TO SCRUBBER
LIME
SLURRY
TANK
20% SOLIDS
138.3 gal/min
HYDRATED
LIME SLURRY
56.5 gal/min
WATER
7.5 hp
15%
SOLIDS
TRANSFER TANK
15 ft 8 in. DIAMETER
LIME SLURRY
PUMPS

Figure 4.5-12. Phillips stabilization and storage system.

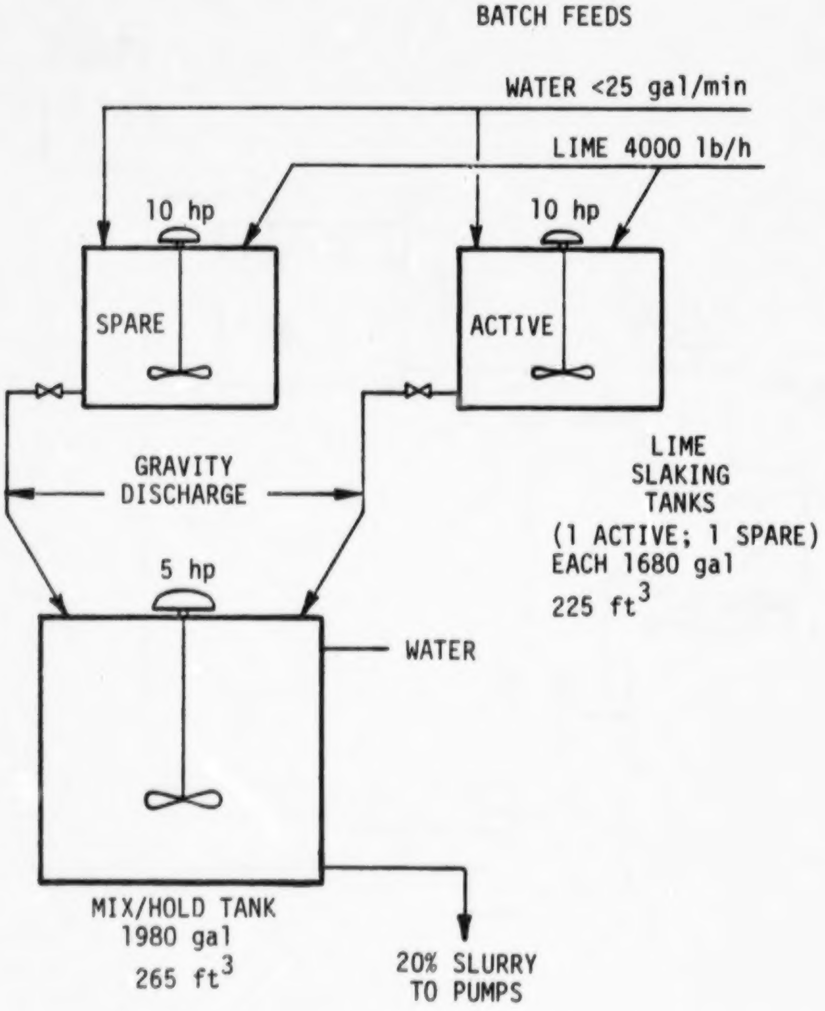

BATCH FEEDS
WATER <25 gal/min
LIME 4000 lb/h
10 hp
10 hp
SPARE
ACTIVE
LIME SLAKING TANKS (1 ACTIVE; 1 SPARE) EACH 1680 gal 225 ft³
GRAVITY DISCHARGE
5 hp
WATER
MIX/HOLD TANK 1980 gal 265 ft³
20% SLURRY TO PUMPS

Figure 4.5-13. Green River slaking and stabilization system.

REFERENCES

1. Laseke, B.A. Survey of Flue Gas Desulfurization Systems: Green River Station, Kentucky Utilities. EPA-600/7-78-048e, March 1978.

2. Private communication with D. Boston, Columbus and Southern Ohio Electric Company, February 1978.

3. Pennwalk Corporation. Preparation and Handling of Lime Slurries. Wallace & Tiernan Division, 1976.

4. Alexander, W., et al. Results of the 170-MW Test Modules Program, Mohave Generating Station. In: EPA Flue Gas Desulfurization Symposium, New Orleans, Louisiana, March 8-11, 1976.

5. Private communication with R. Forsythe and W. Norrocks, Pennsylvania Power Company, February 1978.

6. Private communication with R. O'Hara and J. Mahone, Duquesene Light Company, February 1978.

7. Pernick. S.L. Elrama and Phillips Power Stations Lime Scrubbing Facilities. In: EPA Flue Gas Desulfurization Symposium, New Orleans, Louisiana, March 8-11, 1976.

BIBLIOGRAPHY

Baker, K.J., and R.W. Jordan. Effect of Dissolved Solids in SO_2 Scrubber Water Used for Lime Slaking. In: WWEMA Industrial Pollution Conference, April 1975.

Kunesh, C.J. The Calcination and Slaking of Quicklime. In: International Water Conference, October 1976.

Laseke, B.A. EPA Utility FGD Survey, December 1977 - January 1978. EPA-600/7-78-051a, March 1978.

Pennwalt Corporation. Preparation and Handling of Lime Slurries. Wallace & Tiernan Division.

GLOSSARY

burning: Use of insufficient water during a quicklime slaking operation resulting in a partially slaked, unreactive lime slurry.

dolomitic: Indicates the presence of approximately equal molar amounts of calcium and magnesium in a limestone, quicklime, or hydrated lime.

drowning: Use of too much water or too little agitation during a quicklime slaking operation resulting in a poorly hydrated lime.

feeder: A mechanical device that regulates rate of flow of bulk solids. Also known as dry feeder or dry chemical feeder.

gravimetric: Indicates a measurement on the basis of mass.

hard-burned: Indicates a quicklime manufactured at conditions resulting in low reactivity toward water.

high-calcium: Indicates the presence of less than 5 percent magnesium in a limestone, quicklime, or hydrated lime.

hydrated lime: The material resulting from the reaction between quicklime and water, consisting primarily of calcium hydroxide or a mixture of calcium hydroxide and magnesium oxide and/or hydroxide. Also known as lime hydrate or slaked lime.

hydration: the process of reacting quicklime with water to produce hydrated lime, usually in the form of a dry powder.

lime: A caustic infusible solid that consists of calcium oxide together with magnesia, that is obtained by calcining limestone.

limestone: A sedimentary rock consisting mainly of calcium carbonate or mixture of calcium carbonate and magnesium carbonate.

lime slurry: A more or less viscous slurry formed by slaking quicklime with excess water or by addition of water to hydrated lime. Also known as milk of lime.

magnesian: Indicates the presence of from 5 to 35 percent magnesium in a limestone, quicklime, or hydrated lime.

quicklime: The product of the calcination of limestone, composed primarily of calcium oxide if high-calcium limestone is used or of approximately equal molar amounts of calcium oxide and magnesium oxide if dolomitic limestone is used.

scale: Insoluble or slightly soluble inorganic materials, often crystalline, formed by the reaction of lime with impurities in water or with atmospheric constituents.

slaker: Mechanical equipment designed to produce the slaking reaction.

slaking: The process of allowing quicklime to react with water to produce hydrated lime. In popular usage, slaking indicates use of excess water under conditions of close chemical control to produce a hydrated lime slurry or paste.

soft-burned: Indicates a quicklime manufactured at conditions resulting in high reactivity towards water.

stabilization: The process of holding a freshly prepared lime slurry until all chemical reactions between slurry constituents have approached equilibrium.

volumetric: Indicates a measurement on the basis of volume.

CONTENTS

4.6 SCRUBBER/ABSORBER

Page

4.6.1 Introduction 4.6-1

4.6.2 Industrial Scrubber-absorbers 4.6-1

    4.6.2.1 Tray Absorbers 4.6-1
    4.6.2.2 Packed Absorbers 4.6-3
    4.6.2.3 Moving Bed Absorbers 4.6-4
    4.6.2.4 Venturi Scrubber-absorbers 4.6-4
    4.6.2.5 Spray Scrubber-absorbers 4.6-4

4.6.3 Materials for Construction of Scrubbers 4.6-5

    4.6.3.1 Introduction 4.6-5
    4.6.3.2 Steel and Alloys 4.6-5
    4.6.3.3 Coatings 4.6-10
    4.6.3.4 Rubber Liners 4.6-15
    4.6.3.5 Brick 4.6-17
    4.6.3.6 Conclusions 4.6-19
    4.6.3.7 Existing Facilities 4.6-19

4.6.4 Mechanical Design 4.6-21

    4.6.4.1 Introduction 4.6-21

4.6.5 Scale Formation 4.6-22

    4.6.5.1 Types of Scale 4.6-23
    4.6.5.2 Problems Resulting from Scale Formation 4.6-25
    4.6.5.3 Techniques to Prevent Scale Formation 4.6-26
    4.6.5.4 Effects of Various Factors on Scaling 4.6-27

4.6.6 Process Design Variables 4.6-28

    4.6.6.1 Stoichiometry 4.6-28
    4.6.6.2 L/G Ratio 4.6-29
    4.6.6.3 pH 4.6-29
    4.6.6.4 Increased Gas Velocity 4.6-30
    4.6.6.5 Liquid Distribution 4.6-30
    4.6.6.6 Water Balance 4.6-31
    4.6.6.7 Interfacial Area 4.6-33

CONTENTS (continued)

Page

4.6.7 Existing Facilities 4.6-33

- 4.6.7.1 Louisville Gas and Electric, Cane Run Unit 4 4.6-33
- 4.6.7.2 Louisville Gas and Electric, Paddy's Run Unit 6 4.6-35
- 4.6.7.3 Kentucky Utilities, Green River Power Station 4.6-35
- 4.6.7.4 Duquesne Light, Phillips 4.6-35
- 4.6.7.5 Duquesne Light, Elrama 4.6-35
- 4.6.7.6 Columbus and Southern Ohio Electric, Conesville Unit 5 4.6-36
- 4.6.7.7 Pennsylvania Power, Bruce Mansfield Units 1 and 2 4.6-36

References 4.6-37

4.6 SCRUBBER/ABSORBER

4.6.1 Introduction

In this section, the term "scrubber" is used for the device performing particulate removal as its major function, whereas the term "absorber" is used to describe the device that is primarily designed to remove SO_2. The principal unit operation involved in a lime FGD system is gas absorption by chemical reaction. The SO_2 in the flue gas is absorbed by a lime slurry, which reacts with it chemically. The purpose of the equipment used for the gas-liquid operation (the absorber) is to provide intimate contact of the two fluids in order to facilitate interphase mass transfer of SO_2. The rate of mass transfer is directly dependent on the interfacial surface area (the surface exposed between the two phases), hence the nature and degree of dispersion of one fluid into the other is of prime importance. The equipment may be classified according to whether it disperses either the gas or the liquid; however, the most widely used types of absorbers are classified by the type of internals.

Each type of absorber is discussed with respect to the salient design features, advantages, disadvantages, and the vendors supplying that particular type. Table 4.6-1 gives a summary of existing SO_2 absorbers in the operational lime FGD systems. The degree to which the mass transfer characteristics of an absorber can be utilized and its associated cost will determine the applicability of the absorber for a specific SO_2 removal requirement. Major factors that determine the operating cost are pressure drop and the L/G ratio. Flexibility in the design, which is the ability of the absorber to retain its SO_2 removal efficiency at reduced gas flow rates, is also a major consideration in selection of an absorber.

4.6.2 Industrial Scrubber-absorbers[1,2]

4.6.2.1 Tray Absorbers--

A tray absorber consists of a vertical tower with one or more trays mounted transversely inside. Gas comes in at the bottom of the tower; passes upward through perforations, valves, slots, or other openings in the tray; then bubbles through the liquid to form a froth; disengages from the froth; and passes on to the next tray above. The liquid enters at the top and flows downward by gravity. On its way, it flows across each tray and through a downspout to the tray below. The overall effect is a multiple countercurrent contact of gas and liquid, although each tray is characterized by a crossflow of the two. On each tray the fluids are brought into intimate contact, interphase diffusion occurs, and the fluids are separated.

Table 4.6-1. SO_2 ABSORBERS IN OPERATIONAL LIME FGD SYSTEMS

Unit/Utility	SO_2 Absorber								
	Vendor	Type	L/G at 120°F, gal/1000 acf	Δp, in. H_2O	Internals	Dimensions, ft	Materials of construction		No. of modules per unit
							Absorbers	Internals	
Green River Nos. 1, 2, 3, Kentucky Utilities	American Air Filter	Moving	34	4	Solid spheres, spray nozzles	20 x 20 x 27.5	Mild steel, 3/4-in. acid-proof lining	PVC balls, ceramic nozzles	One for all the three units
Bruce Mansfield Nos. 1, 2 Pennsylvania Power	Chemico	Venturi	60	16	Plumb bob	35 (dia.) x 50	Mild steel, polyester flakeglass lining	316L SS Ceilcoted	6
Cane Run No. 4 Louisville G&E	American Air Filter	Moving bed	55 - 65	4	Solid spheres, 1-1/4-in. (dia.) spray nozzles	20 x 20 x 27.5	Mild steel, 3/4-in. acid proof lining	Polyurethane balls, ceramic nozzles	2
Paddy's Run No. 6 Louisville G&E	Combustion Engineering	Moving bed	15 - 18	12	Marbles, 1 in. (dia.); 3-in. (deep) bed	17 x 18 x 50	Mild steel, 2-1/2-in. thick flake lining	Glass, 316 SS supports	2
Elrama Duquesne Power	Chemico	Venturi	40	16	Upper cone brill nozzle, spray nozzles	30 (dia.) x 60	Mild steel, Ceilcoted	316L SS, Ceilcoted	5
Phillips Duquesne Power	Chemico	Venturi	40	16	Upper cone, bull nozzle, spray nozzles	45 (dia.) x 50	Mild steel, Ceilcoted	316L SS, Ceilcoted	5
Conesville No. 5 Columbus & Southern	UOP	Moving bed	50	6	Hollow spheres, 1 in. (dia.); 2-in. (deep) bed		Mild steel, rubber lined	Neoprene balls	2

The number of theoretical trays in a tower is dependent only upon material balance and equilibrium considerations. The tray efficiency, and therefore the number of actual trays, is determined by the mechanical design and the operating conditions. The diameter of the tower is principally determined by the quantities of liquid and gas flowing through the tower per unit time. Once the number of theoretical trays is determined, optimization of absorber design is based on several opposing factors described below.

Deep pools of liquid on the trays lead to high tray efficiencies because of long contact time, but also lead to high pressure drop per tray and a possibility of flooding, a condition in which liquid may fill the tower resulting in high liquid carryover by the effluent gas and slugs of foam. High gas velocities, within limits, provide good vapor-liquid contact through excellence of dispersion, but lead to excessive entrainment and high pressure drop. The general design procedure involves selection of design configurations, based on experience followed by calculations to ensure that the pressure drop and the flexibility are satisfactory.

At present, none of the utility lime FGD systems uses a tray absorber, primarily because of the severe plugging problems associated with lime slurry handling through a close tortuous path. The tray absorbers are, however, extensively used in other industrial boiler FGD systems, such as those using sodium-based alkali absorption, most of which are supplied by Koch Engineering and FMC Corporation. Babcock and Wilcox has also supplied tray absorbers at some of the utility limestone FGD systems.

4.6.2.2 Packed Absorbers--

Packed towers, used for continuous countercurrent contact of liquid and gas, are vertical columns filled with packing. The liquid trickles down through the packed bed, thus forming a film of large surface area to contact the gas. The gas stream to be cleaned typically flows upward through the packing. The desirable properties for tower packings are larger specific packing surface (the surface area per unit volume of packed space), high fractional void volume, low density but high structural strength, chemical inertness to the fluids being processed, and low cost.

Packed tower absorbers are also not used at any of the utility lime FGD systems because of their vulnerability to plugging. The plugging problem has been alleviated in a modification of the packed absorber, the moving bed absorber described below. In industrial boiler FGD systems using sodium and ammonia absorption, packed absorbers are offered by the Ceilcote Company and Chemico, respectively.

4.6.2.3 Moving Bed Absorbers--

Moving bed absorbers provide a zone of mobile packing, usually plastic or glass spheres, where gas and liquid can intimately mix. The absorber shell holds the perforated plate on which the movable packing is placed. Gas passes upward through the packing while liquid is sprayed up from the bottom through the perforated plate, and/or down on top of the moving bed. Because of the high gas velocity, the packing material moves around constantly when the scrubber is operating. This movement makes the bed turbulent and keeps the packing clean. The pressure drop of a moving bed is typically 2.8 to 5.9 in. H_2O per stage.

The major vendors offering moving bed absorbers for utility FGD systems are American Air Filter and UOP. Combustion Engineering has discontinued this type of absorber only recently.

4.6.2.4 Venturi Scrubber-absorbers--

Venturi scrubber-absorbers are towers with spray devices that utilize a moving gas stream to atomize liquid drops, and then accelerate these drops through the throat of a venturi. High gas velocity is used to produce a high relative velocity between gas and liquid, which promotes particle collection. The scrubbers usually have a variable throat, whereas the absorbers often have a fixed throat. High pressure drop venturi scrubbers can collect particles with high efficiency; however, mass transfer characteristics are limited because of the cocurrent nature of the gas-liquid flow.

Two notable modifications to the conventional converging-diverging design of the venturis are annular orifice and rod bank towers. In the annular orifice tower, which has the converging section and the throat, gas impinges on a movable disc while liquid flows cocurrently down the walls of the converging section. In the rod bank tower, gas and liquid flow cocurrently through the throat across several runs of rods, which usually have adjustable spacing.

Chemico offered venturi scrubber-absorbers in the early utility FGD systems. Combustion Equipment Associates still offers this type of scrubber-absorber in utility FGD systems.

4.6.2.5 Spray Scrubber-absorbers--

A spray scrubber utilizes spray nozzles for liquid droplet atomization. The sprays are directed such that the gas passes upward through the descending atomized liquid droplets. If the tower is vertical, the relative velocity between the droplets and the gas is eventually the terminal settling velocity of the droplets. Most droplets eventually hit the walls in a tall tower. Spray absorbers can also be used in horizontal configuration. The flow of gas and liquid is, then, crosscurrent. An EPRI report on the evaluation of a horizontal scrubber and application in a 1-MW pilot plant at the Colbert Station of the Tennessee Valley Authority will be published in late 1978. Cocurrent horizontal and vertical absorbers are also being investigated.

Spray towers are used for both particle collection (scrubbers) and mass transfer (absorbers). They generally have low pressure drop and high liquid flow rate and are the least expensive type of absorber in terms of capital expense. Particle collection is limited by the terminal settling velocity and diameter of the spray droplets.

Chemico, Combustion Engineering, Combustion Equipment Associates, M.W. Kellogs, and Peabody Engineering are the leading FGD vendors who offer spray absorbers preceded by an ESP for particulate collection.

4.6.3 Materials for Construction of Scrubbers

NOTE: Much of the information contained within Section 4.12 of this data book is also pertinent to the following discussion.

4.6.3.1 Introduction--

The choice of materials for the construction of scrubbers and abosrbers is complex and depends on many variables, which include the planned life of the unit, operation of the unit, economic considerations, safety considerations, and the unit location and environment.

The type of corrosion varies depending on the location in the scrubber or absorber. For example, the venturi throat is susceptible to high abrasion and hence suffers from erosion-corrosion, whereas general corrosion is a major problem downstream from the mist eliminator. Operating conditions at particular locations in the module are an important factor in material selection for a scrubber or absorber.

4.6.3.2 Steel and Alloys[3,4,5]--

Spool tests have been performed in several FGD systems by placing the spools in various locations in the scrubber. The test data given in Tables 4.6-2 and 4.6-3 were reported by Tennessee Valley Authority.[3] The test conditions and the analyses of different types of steel and other alloys are given in Tables 4.6-4 and 4.6-5 respectively.

Table 4.6-2. VENTURI THROAT CORROSION SPOOL TEST DATA[3]

Specimens: Round, machined-edge spool pieces 2 in. O.D. x 23/64 in. I.D. x approximately 11 gauge. Single air annealed cross weld. Insulated Teflon separators.

Temperature: 80° to 170°F

Duration of test: 2370 hours

Material	Corrosion rate,[a] mils/yr
Allegheny Metal 6X	20
Allegheny Metal 29-4	14
Mild steel, ASTM-285	>1855
Climax 18-2	32
Hastelloy C-276	44
Haynes Alloy 6B	9
Inconel 625	29
Jessop 700	31
Multimet	26
Nitronic 50M	16
Stainless T-216	12
Stainless T-316L (2.3% Mo)	12
Stainless T-316L (2.8% Mo)	10
Stainless T-317L	9
U.S.S. Cor-Ten A	>2120
Zirconium 702	6

[a] Based on general corrosion attack.

Table 4.6-3. SCRUBBER CORROSION SPOOL TEST DATA BELOW AND ABOVE THE MIST ELIMINATOR

Specimens: Round, machined-edge spool pieces 2 in. O.D. x 23/64 in. I.D. x approx. 11 gauge. Single air-annealed cross weld. Insulated Teflon separators.

Temperature: 80° to 170°F

Material	Below the mist eliminator[a]		Above the mist eliminator[b]	
	Corrosion rate,[a] mils/yr	Pitting, mils	Corrosion rate,[c] mils/yr	Pitting, mils
Allegheny Metal 6X	<0.05	–[d]	<0.05	17
Allegheny Metal 29-Y	0.05-0.49	–	0.05-0.49	–
Mild steel, ASTM-285	171	5	26	5
Climax 18-2	0.05-0.49	10	<0.05	6
Hastelloy C-276	<0.05	–	<0.05	–
Hastelloy G	0.05-0.49	–	0.05-0.49	–
Haynes Alloy 6B	–	9	<0.05	–
Inconel 625	0.05-0.49	–	<0.05	–
Jessop 700	–	7	<0.05	–
Multimet	<0.05	–	<0.05	–
Nitronic 50M	0.05-0.49	4	1.0	–
Stainless T-316L (2.3% Mo)	0.05-0.49	–	1.0	–
Stainless T-316L (2.8% Mo)	<0.05	–	0.05-0.49	–
U.S.S. Cor-Ten A	170	–	43	11
Zirconium 702	<0.05	–	<0.05	–

[a] Test duration 220 h, 5000 ppm MgO added to the slurry

[b] Test duration 1490 h, 5000 ppm MgO added to the slurry

[c] Based on general corrosion attack.

[d] Indicates negligible corrosion rate or pitting.

Table 4.6-4. CONDITIONS FOR THE CORROSION TESTS AT THE SHAWNEE STATION OF TVA[3]

	Test spool location		
	Venturi throat	Before mist eliminator	After mist eliminator
Gas temperature, °F	80-170	125-130	125-130
Gas velocity, ft/s	40-100	4.5-9.4	4.5-9.4
Gas flow rate, 1000 acfm at 330°F	15-30	15-30	15-30

Gas composition	Component	% by volume
	SO_2	0.2-0.4
	CO_2	10-18
	O_2	5-15
	H_2O	8-15
	HCl	0.01
	N_2	74
	Fly ash, gr/scf	2-7

Table 4.6-5. CHEMICAL ANALYSIS OF ALLOYS[3]

Alloys	Chemical analysis, %									
	C	Cr	Ni	Fe	Cu	Mo	Mn	Si	P	S	Others
Al 6X[a]	0.027	20.32	24.17	Bal.		6.42	1.46	0.56	0.023	0.004	N, 0.03
Al 29-4[a]	0.004	29.3	0.12	Bal.		3.95	0.10	0.05	0.013	0.013	N, 0.010
Climax 18-2[a]	0.016	18.44	0.39	Bal.	0.21	2.08	0.4	0.39			N, 0.013; Ti, 0.33
Cor-Ten A[a]	0.11	0.66	0.33	Bal.	0.36		0.39	0.44	0.098	0.026	
Hastelloy C-276[a]	0.002	15.87	Bal.	5.96		16.32	0.49	<0.01	0.012	0.010	Co, 1.84; W, 3.51; V, 0.25
Hastelloy G[a]	0.02	21.72	Bal.	18.68	1.77	6.69	1.30	0.34	0.021	0.011	Co, 1.57; Cb + Ta, 2.13; W, 0.54
Haynes 6B[a]	0.96	29.75	2.13	2.36		1.08	1.40	0.36			Co, Bal.; W, 4.30
Inconel 625	0.1[b]	20-23	Bal.	5.00[b]		8-10	0.5[b]	0.5[b]	0.015[b]	0.015[b]	Co, 1.0[b]; Cb + Ta, 3.15-4.15; Al, 0.4[b]; Ti, 0.4[b]
Jessop 700	0.03	21.00	25.00	Bal.		4.5	1.70	0.50			Cb, 0.30
Mild steel A-285	0.35[b]			Bal.	0.35[b]		0.80[b]		0.05[b]	0.05[b]	
Multimet	0.2[b]	18-22.5	18-22	Bal.		2.75-3.75					Cb, 0.75-1.5; Co, 18-22, N, 0.1-0.2; W, 2-3
Nitronic 50M	0.06[b]	21	14	Bal.		1.5-3.0	6	1.00[b]	0.04[b]	0.03[b]	N, 0.2-0.4; Cb, 0.1-0.3; V, 0.1-0.3
Type 216 SS[a]	0.069	19.54	6.77	Bal.		2.31	8.21	0.23	0.023	0.005	N, 0.358
Type 316L SS[a]	0.020	17.1	13.8	Bal.	0.07	2.3	1.30	0.49	0.016	0.016	
Type 316L SS[a]	0.025	18.0	13.9	Bal.	0.05	2.77	1.38	0.54	0.011	0.012	
Type 316L SS[a]	0.022	18.61	13.62	Bal.	0.45	3.16	1.62	0.60	0.021	0.009	B, 0.0008; Cb, 0.02; Co, 0.17; N, 0.065; Al, 0.012; Ti, 0.004
Zirconium 702	0.015	c		c							N, 0.05; Hf, <0.10; Zr + Hf, >99.2

[a] Analysis was supplied with the material.

[b] Maximum.

[c] Cr + Fe, 0.10% by weight.

In the venturi throat, the greatest attack on the specimens was due to erosion-corrosion. The high velocity of the lime slurry, containing fly ash, SO_2, CO_2, and HCl, accounted for the high rates of deterioration. Specimens of Cor-Ten A and mild steel, which were completely destroyed, had penetration rates greater than 1850 mils/yr. The most promising alloys in the order of decreasing resistance to erosion-corrosion were Zirconium 702, Maynes 6B, Type 317L, AL 29-4, and AL 6X.

In the recirculation tank, the corrosion rates of mild steel and Cor-Ten A were 35 and 26 mils/yr. Attack on the other alloys was negligible. During this particular series of tests, the attack on mild steel and Cor-Ten A varied greatly in the scrubber tower.[3] In the earlier tests, corrosion of the specimens exposed in the top of the tower was greater than it was for specimens exposed near the middle and bottom. However, during the fourth series, corrosion was less for the specimen near the mist eliminator. The installation of an automatic spray system for washing the mist eliminator also washed the test spools. At other test locations,[4,5] where the stainless steel specimens were coated with deposits of solids, pitting occurred more frequently.

4.6.3.3 Coatings[6-13]--

Many types of coating are available for use in FGD systems. The following list shows the basic types of resin that can be used in a scrubber.

- Bituminous
- Chlorinated rubber
- Coal tar epoxy
- Epoxy
- Polyester
- Polyurethane
- Vinyl ester
- Furan
- Phenolic

Of these resins, polyester, bituminous, epoxy, vinyl ester, and furan are the most common ones found in utility FGD systems.

Furan, polyester, epoxy, and vinyl ester resins can be applied as a coating by themselves, with glass flakes, or with a fabric mat. Glass flakes are added to the resins to reduce permeability, add strength, and minimize the possibility of pinholes in the coating. A fabric mat is used with a resin to increase the strength of a coating. Tables 4.6-6 through 4.6-9 show some physical characteristics of furan, epoxy, vinyl ester, and polyester resins, respectively, with and without glass flakes or a fabric mat.[6]

Table 4.6-6. TYPICAL CHARACTERISTICS OF FURAN RESINS[6]

Properties	Resin	Flake glass	Fabric reinforced
Tensile strength, psi	1,200	1,250	8,150
Coefficient of expansion, in./in./°F	2.0×10^{-5}	1.4×10^{-5}	1.5×10^{-5}
Barcol hardness	NR[a]	28	20
Temperature resistance, °F	350	125	125
Flexural strength, psi	3,800	2,660	19,850
Abrasion resistance, Taber Wear Index	NR	83	57

[a] NR - Not reported.

Table 4.6-7. TYPICAL CHARACTERISTICS OF EPOXY RESINS[6]

Properties	Resin	Flake glass	Fabric reinforced
Tensile strength, psi	1,800	3,350	3,400
Coefficient of expansion, in./in./°F	3.0×10^{-5}	1.5×10^{-5}	1.9×10^{-5}
Barcol hardness	NR[a]	40	45
Temperature resistance, °F	175	160	180
Flexural strength, psi	3,800	6,735	9,500
Abrasion resistance, Taber Wear Index	NR	129	140

[a] NR - Not reported.

Table 4.6-8. TYPICAL CHARACTERISTICS OF VINYL ESTER RESINS[6]

Properties	Resin	Flake glass	Fabric reinforced
Tensile strength, psi	2,300	2,300	6,700
Coefficient of expansion, in./in./°F	1.6×10^{-5}	1.5×10^{-5}	1.5×10^{-5}
Barcol hardness	NR[a]	38	50
Temperature resistance, °F	180	160	160
Flexural strength, psi	4,200	6,000	10,500
Abrasion resistance, Taber Wear Index	NR	167	185

[a] NR - Not reported.

Table 4.6-9. TYPICAL CHARACTERISTICS OF POLYESTER RESINS[6]

Properties	Resin	Flake glass	Fabric reinforced
Tensile strength, psi	2,300	2,050	6,600
Coefficient of expansion, in./in./°F	1.9×10^{-5}	1.5×10^{-5}	1.5×10^{-5}
Barcol hardness	NR[a]	42	52
Temperature resistance, °F	225	160	160
Flexural strength, psi	4,800	6,100	12,200
Abrasion resistance, Taber Wear Index	NR	177	187

[a] NR - Not reported.

Polyester coatings have some excellent characteristics required of scrubber liners but have had only fair results in the field. Polyester resins have excellent resistance to acid and good resistance to heat and abrasion. However, there have been reported failures of the polyester coating in the scrubbers and ducts at one utility where the polyester decreased in hardness, lost its adhesive properties, and several blisters formed.[7]

Vinyl resins have been improved to the point where vinyl esters have better properties than polyesters. An unreinforced sprayable vinyl ester resin is reported to be able to withstand temperatures up to 400°F continuously, to have superior abrasion resistance, and to resist acids. Vinyl ester coatings have been applied to stacks, ducts, and scrubbers and have adequately handled the scrubbing system environment.

Epoxy resin coatings have done well in a pilot plant study. They have less resistance to acids than do other resins, but adhere to metals better and have a higher tensile strength. They have good elastic properties.

Furan resins have low temperature limit, tensile strength, and abrasion resistance, and are brittle and shrink when applied over a large area. Furan resins do have a superior resistance to acids and are very strong when reinforced with a fabric mat. In a pilot plant test, furan resins did well in all areas except immediately above the mist eliminator.

Precrete, an inexpensive coating, has been used by Kentucky Utilities and Louisville Gas and Electric Company to prevent corrosion of stacks, ducts, and scrubbers of their FGD systems. Precrete dissolves at a constant rate, so a thick layer can be applied and its life expectancy can be predicted. However, recoating requires extensive downtimes.

4.6.3.4 Rubber Liners[14]--

There are a number of types of rubber liner, but natural and neoprene rubber liners are most commonly used in a scrubber or absorber. Natural rubber is softer, more resilient, and has more tear resistance than neoprene rubber; however, neoprene provides more corrosion resistance and can withstand higher temperatures.[14] Table 4.6-10 shows some of the characteristics of both materials.

Neoprene and natural rubber liners have been tested by Bechtel and TVA in the scrubber of an FGD system.[7] The results show natural rubber is superior. The natural liner withstood the design scrubber environment, and there were no signs of general corrosion or erosion. Neoprene rubber liners did show wear from erosion in the area where the flue gases entered the scrubber. The neoprene liner also formed some blisters after 3 years of operation.

Table 4.6-10. PROPERTY CHARACTERISTICS FOR NATURAL RUBBER AND NEOPRENE RUBBER[9]

Property	Natural rubber	Neoprene rubber
Hardness range (share "A")[a]	40 - 100	30 - 90
Tensile strength, psi[a]	4500	3500
Maximum elongation, %	900	1000
Abrasion resistance	Excellent	Very good
Maximum ambient temperature allowable °F	160	225
Resilience	Excellent	Very good
Aging resistance	Good	Excellent
Flame resistance	Poor	Good
Tear resistance	Excellent	Good

[a] Indicates values for soft rubber. Values run higher for hard rubber.

Rubber liners do have disadvantages. They are susceptible to adhesion losses, mechanical damage, wear due to abrasion, and fire. Overheating can cause adhesion losses and substrate exposure to the corrosive environment. Rubber liners can be torn or cut; this may be caused by material in the flue gases, during operation, installation, or when other equipment is installed or removed. Natural rubber can withstand abrasion better than neoprene rubber, but neither can withstand the abrasion in the venturi throat. Rubber liners are not flame resistant, so extreme care must be exercised when welding near them.

4.6.3.5 Brick[12,14]--

There are many types of brick: those most commonly used in FGD systems are red shale, fire clay, and silicon carbide. Each of these bricks has limitations that restrict its use. Red shale should be used where minimum permeation of liquor through the brick is required and thermal shock is not a factor. Fire clay should be used where thermal shock is a factor and minimum permeation is not required. Silicon carbide brick should be used where high abrasion resistance is required.

Red shale brick is a type "L" and fire clay is a type "H" brick under the "Specification for Chemical Resistant Masonry Units," ASTM C279. Typical properties meeting type "H" and "L" bricks are shown in Table 4.6-11.

In the venturi throat, silicon carbide brick in conjunction with furan resin mortar should prove to be a suitable construction material. It can withstand the abrasion due to particulate matter in the flue gases.

Fire clay brick can be used above the mist eliminator and at the inlet to the absorber. In the absorber inlet, the slurry from the sprays does not contact the gases, and above the mist eliminator the mist in the flue gases is minimal; therefore, fire clay brick with a furan resin mortar is recommended.

In the main section of the absorber, red shale brick could be used. This section is normally in contact with the slurry, and the temperature of the flue gases is reduced. A furan resin should be used as the mortar lining.

Corrosion-resistant brick alone will not protect the scrubber shell from corroding. An impervious membrane must be applied between the scrubber shell and brick. The purpose of the brick is to protect the membrane from abrasion and excessive heat. The membranes are made from vinyl resins, natural and synthetic rubbers, or asphaltic materials.

Table 4.6-11. PROPERTIES OF TYPE "H" AND "L" BRICKS[14]

Designation	Minimum modules of rupture (brick flatwise), psi		Maximum water absorption by 2-h boiling test, %	
	Average of five bricks	Individual	Average of five bricks	Individual
Type "H"	1250	1000	6.0	7.0
Type "L"	2500	2000	1.0	1.5

4.6.3.6 Conclusions--

Spool tests and actual field data have shown that T-316L stainless steel can withstand corrosion and high temperatures and can handle relatively high chloride and sulfuric acid concentrations. It should be noted, however, that stainless steels are susceptible to stress corrosion in chloride environments. The T-316L stainless steel is the cheapest metal that can withstand the abrasive, acidic environment of the scrubber-absorber section for the expected life of the lime FGD system.

Precrete is an inexpensive coating that acts as an impermeable body. Because of its high corrosion rate, however, a thick layer of precrete must be applied. Since it is so inexpensive, the precrete is still a viable option for use as a liner. It also has an added benefit in that the life expectancy of the coating can be predicted. However, relining can take considerable time. This must be allowed for in the planned availability of the system, either by reducing demand on the system or by building in some redundancy.

4.6.3.7 Existing Facilities[15-19]--

Paddy's Run Station[15,16]
Unit for: Boiler 6
Owned by: Louisville Gas and Electric Company

The FGD system at the Paddy's Run plant was supplied by Combustion Engineering. The scrubber shell is made of mild steel. An 80-mil coat of Ceilcote 156 (flakeglass) was applied to the scrubber internals. This lining has eroded in areas of high abrasion, where the flue gases and where the lime slurry enter the scrubber. When the Ceilcote lining wears away, it is patched with the same coating.

Cane Run Station[15,16]
Unit for: Boiler 4
Owned by: Louisville Gas and Electric Company

The lime FGD system for Boiler 4 at the Cane Run plant was supplied by American Air Filter. The scrubber shell is made of mild steel and was initially coated with a Ceilcote lining. When the Ceilcote lining failed in the lower portion of the scrubber, it was replaced with a 2-in. coat of precrete. Precrete was selected as the coating material since it is impermeable. Precrete was applied in a thick coat to allow for the expected high failure rate. Above the mist eliminator to the top of the scrubber, the Ceilcote coating was replaced with Plasite 4005.

Green River Station[16,17]
Units for: Boilers 1, 2, and 3
Owned by: Kentucky Utilities

The Green River FGD system is a variable venturi throat scrubber. The venturi is built of T-316 stainless steel and lined with acid brick. The scrubbing module is built of T-316 stainless steel and was initially coated with a carboline liner. This was replaced when the liner flaked off. This flaking was caused by improper sandblasting. There was too much material remaining on the steel for the coating to adhere to it after sandblasting. In 1977, American Air Filter applied a precrete liner to the scrubber.

Conesville Station[16,18]
Unit for: Boiler 5
Owned by: Columbus and Southern Ohio Company

The FGD system for Boiler 5 consists of two identical scrubbing modules. The scrubber shell is made of mild steel and lined with 1/4 in. of neoprene rubber.

A major fire in scrubbing module 5A in December 1976 caused extensive damage to the internal components of the scrubber; the neoprene liner was destroyed. The module has since been rebuilt and was put into service in May 1978. Columbus and Southern Ohio has had problems with the adhesion of the liner to the steel due to poor application procedures.

Phillips Station and Elrama Station[16,19]
Units for: Two boilers at the Elrama Station
Boilers 1 through 5 at the Phillips Station
Owned by: Duquesne Light and Power Company

The FGD systems at the Phillips Station and Elrama Station are identical. The venturi scrubbers and absorbers are built of mild steel. The venturi throat is lined with 316L stainless steel and no corrosion problems have occurred in this area. The scrubber was initially coated with the flake glass resin Ceilcote 103. The Ceilcote 103 coating did a good job of preventing corrosion when high calcium lime was used. The high calcium lime produced a 1/4- to 1/2-in. scale buildup on the walls of the scrubbers. The scale deposit, in addition to the Ceilcote 103 coating, prevented corrosion. The lime scrubbing system has switched from high calcium lime to Thiosorbic lime. The new lime removed the scale deposits and corroded the Ceilcote 103 coating. Since this coating could not withstand the scrubber environment, Carboline 505 AR coating was applied.

4.6.4 Mechanical Design

4.6.4.1 Introduction--

General characteristics of each scrubber type are discussed in Section 4.6.1. In this section, we will discuss special features that are often overlooked during scrubber design. Consideration of these features will help during troubleshooting and maintenance periods.

Ease of cleaning out the scrubber/absorber--Depending on the type of scrubber/absorber, scale/mud deposits occur at various locations. Deposits are especially a problem at the wet-dry interface since they dry out very quickly. This eventually leads to plugging. The spray tower is much less vulnerable to plugging compared with the packed tower or venturi scrubber. Thus, in the selection of a sizable system, the ease with which it can be cleaned free of scale is an important consideration.

Access to scrubber/absorber internals--Complete cleaning of lime scrubbers may be required as much as every other month. Each cleaning with minor maintenance can require several man-hours. Deposits can occur in and around the throat of the venturi scrubber, which can result in a higher pressure drop through the system. Higher pressure drop decreases the amount of gas that can be scrubbed to such an extent that the generating capability of the power plant is reduced and a cleaning outage becomes necessary. Thus, if consideration is given to easy access when the scrubber is designed, many man-hours can be saved and prolonged outage can be avoided.

Manholes can be installed at each stage of the scrubber for easy access during the maintenance period. Similarly, side doors should be located in the reaction tank so maintenance personnel can get in with jack hammers. Tons of deposits may have to be removed per maintenance period, hence doors should be large enough for easy removal of such a quantity of mud.

Pump suction line--Slurry flow from the scrubber to the thickener can be directed in two different ways: (1) by installing a pump to bleed the slurry from the point near the bottom of the reaction tank, or (2) by taking a slip stream from the recycled slurry stream. The first option is recommended for lime scrubbing systems because the pump can be designed to carry forward big chunks of solids that have settled at the bottom of the reaction tanks. If the second option were followed, big chunks of solids would build up in the reaction tank and cause operational problems and increase the maintenance time during scrubber shutdown. Furthermore, chunks of suspended solids could easily be carried away to the spray area and clog the nozzles.

Drain line--In time solids build up in the reaction tank as in the other portion of the lime scrubbing system. During the scrubber maintenance period, the reaction tank should be completely drained and cleaned. It is therefore necessary to install drain lines to empty the reaction tank.

View plates--View plates can be useful if installed at each stage of the scrubber. It is difficult to observe anything in the scrubber when it is in operation; however, deposits and/or mechanical problems can be observed through the view plates when the system is shut down.

Spray nozzles--Ceramic nozzles have performed well in lime scrubbing systems. Strainers should be installed in the main slurry line to avoid plugging of nozzles. There is always a possibility of plugging these strainers, hence they should be installed around the recirculation pump suction.

Nozzle pluggage can lead to reduced fly ash, SO_2, and SO_3 removal. This can result in a rapid buildup of acidic fly ash on mist eliminator, reheater, and fan. Thus it is very important to clean spray nozzles during regular scrubber maintenance.

4.6.5 Scale Formation

Scaling in lime scrubbing systems can be defined as the tendency of slurry solids to adhere to the surfaces. Scaling has been a major factor contributing to poor reliability in the operation of full-scale scrubbing systems. Scrubber internals and mist eliminator surfaces are areas most susceptible to scaling.

One of the main trouble spots for scaling is the point at which the gas passage walls (duct or scrubber) change from a dry to wet condition. Deposited mud tends to dry out at that point and eventually becomes very hard, difficult to remove material. The usual remedy is to use a soot blower or wash water lance to blow or wash away these deposits into the scrubber. To remedy scaling in other portions of the scrubber, however, is much more difficult and complicated. In these cases the best solution is to prevent mud deposits by chemistry control.

Scaling is a very complex phenomenon with many interrelated factors affecting it. It is beyond the scope of this book to give a complete treatise on the subject of scale formation. This section deals with various types and causes of scale formation and prevention measures. The impacts of various factors on scale formation will be discussed concisely.

4.6.5.1 Types of Scale--

Scaling in lime scrubbing systems can be caused by the reaction products calcium sulfite, calcium sulfate, and calcium carbonate. Of these, sulfate scaling is normally the most difficult to control; however, sulfite and carbonate scale must also be considered in system design.

In a typical lime scrubbing system, a large amount of slurry enters the scrubber at the top, flows downward in contact with the gas, passes to a reaction tank (where fresh absorbent is added), and returns to the scrubber. A bleed stream flows from the reaction tank to a thickener or waste pond, where the product solids settle out and the supernatant liquor is returned to the scrubber system.

In such an arrangement, the slurry circulating through the scrubber generally contains crystals of both calcium sulfite and calcium sulfate. Sulfite is formed in the scrubber and goes in and out of solution as the pH changes. Sulfate, which is not affected much by pH, forms both in the scrubber and the reaction tank by oxidation of sulfite and crystallizes whenever the supersaturation gets so high that the solution can no longer hold it. The crystallization occurs preferably in the reaction tank, where it ordinarily does no harm, but it can occur in the scrubber and either plug gas flow openings or form masses that eventually drop off and plug the liquor circulation system.

Calcium sulfite scaling--Calcium sulfite ($CaSO_3 \cdot 1/2H_2O$) scale is a soft, relatively soluble scale that can be removed from scrubber internal surfaces by a water jet arrangement. This scale is formed in the scrubber under certain pH conditions. These conditions are apparent when one considers the sulfite-bisulfite equilibrium and compares the relative solubilities of the corresponding calcium salts.[20] Extremely soluble bisulfite in solution changes to relatively insoluble sulfite when the solution pH shifts from 4 to 10. When SO_2 is absorbed, the scrubber solution is usually between pH 4 and 6; therefore, the predominant species is bisulfite. Crystallization of calcium sulfite occurs when the pH is suddenly raised either in localized areas or in a reaction tank (Figure 4.6-1). These calcium sulfite crystals then may attach to surfaces and form scale.

Calcium sulfate scaling--Calcium sulfate ($CaSO_4 \cdot 2H_2O$) scale is a hard, relatively insoluble scale that cannot be removed from scrubber internal surfaces except by hammering and chipping. This scale is formed in the system as a result of oxidation in the scrubber, reaction tank, and thickener. Unlike sulfite, pH gradient in the scrubber does not help hold sulfates in solution.

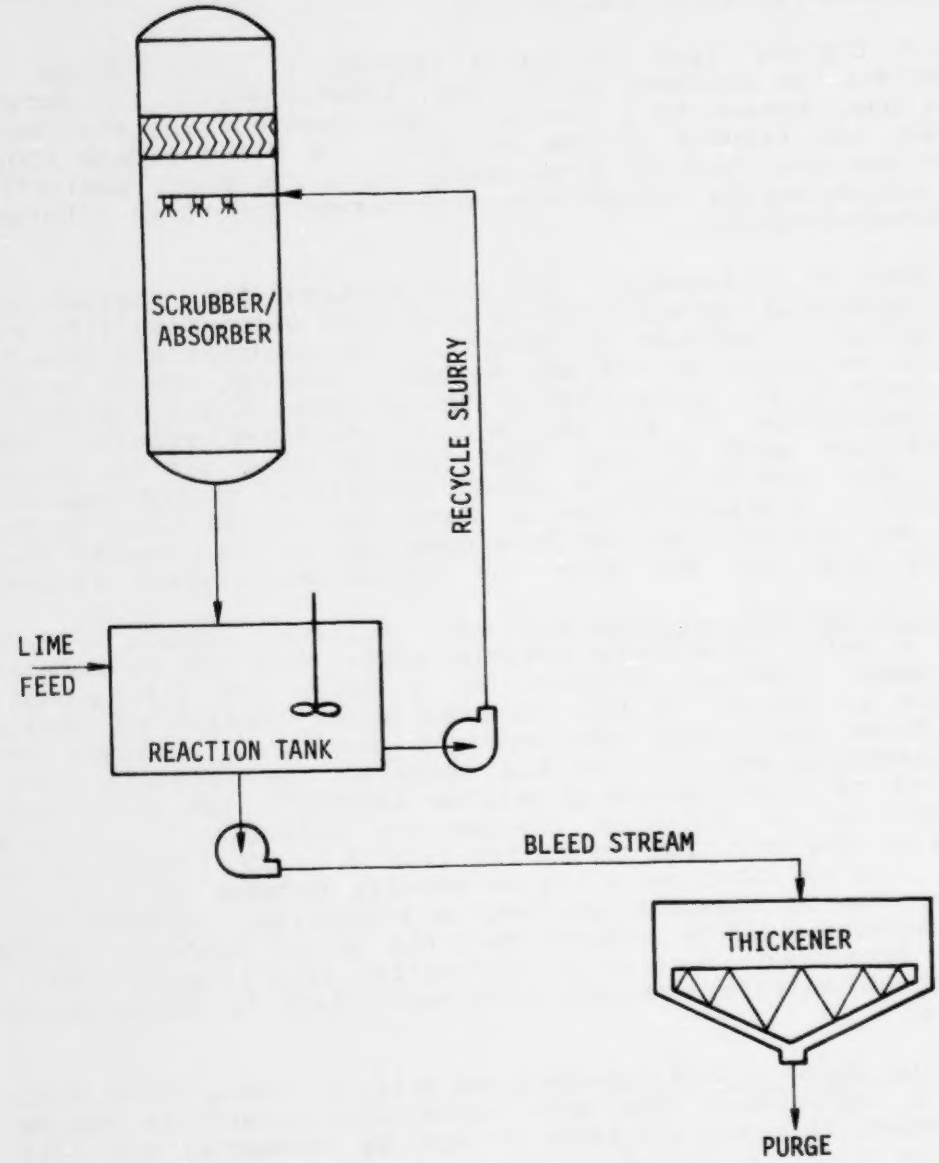

SCRUBBER/
ABSORBER
RECYCLE SLURRY
LIME
FEED
REACTION TANK
BLEED STREAM
THICKENER
PURGE

Figure 4.6-1. Arrangement of the reaction tank with respect to scrubber/absorber and thickener.

Calcium sulfate will begin to precipitate whenever its saturation limit is exceeded, or, in other words, whenever the relative saturation is greater than 1.5.[20] The ratio of the products of the activities of Ca^{++} and $SO^{4=}$ to the solubility product constant (K_{sp}) as a measure of the degree of saturation is termed the relative saturation (RS). For further discussion of chemical activities, the reader is referred to any standard thermodynamics text or Perry's Handbook of Chemical Engineering, Fifth Edition (pp. 4-54).

$$RS = \frac{A_{Ca^{++}} A_{SO_4^=}}{K_{sp\ (CaSO_4 \cdot 2H_2O)}}$$

when:

RS < 1.0 solution is subsaturated;
RS = 1.0 solution is saturated;
RS > 1.0 solution is supersaturated.

Calcium carbonate scaling--Calcium carbonate ($CaCO_3$) scale is a soft and easy to remove scale. This, together with calcium sulfite scale accumulates especially downstream from sudden expansions and along the walls where irrigation is low.

It has been shown in small-scale tests that a high-pH lime slurry fed to the scrubber can react with CO_2 in the gas with resulting scaling of calcium carbonate on scrubber surfaces. The net situation is obscured by the fact that high pH can also cause sulfite crystallization. Because of this, it is not clear whether carbonate scaling is a significant problem or not.

4.6.5.2 Problems Resulting From Scale Formation--

Scale formation can require a scrubber shutdown when screens, piping, nozzles, packing material, mist eliminator blades, or liquid distribution grids plug up with so much scale that pressure differentials increase and flow rate capacities are reduced. Scale formation can also occur in instruments and sensor lines such as pH sample taps, pressure differential sensors, level indicators, pressure gauges, and gas sampling taps to the extent that the scrubbing system cannot be operated as a reliable means of control.

Plugging due to scale formation can occur suddenly during an upset condition or can accumulate and build up over a long interval of operating time. Whenever scrubbers are shut down for periods longer than a few hours, and the soft accumulations are not immediately washed away, the soft scale begins to dry and forms a much harder scale. Scale can cause accelerated corrosion either by concentrating electrochemical attack beneath a layer of scale deposited on metallic surfaces or by damaging protective coatings when scale chunks fall off--thus leading indirectly to accelerated corrosion at the point of damage. Even stainless steel material can be severely damaged by stress-corrosion attack and pitting underneath scale deposits, especially if the scrubber slurry contains a high concentration of chloride in solution from chloride in the coal or makeup water.

Scale formation also can significantly influence gas flow distribution, especially in the mist eliminator area where a uniform gas distribution is critical for preventing high local velocities and subsequent carrythrough of solids and liquids.

4.6.5.3 Techniques to Prevent Scale Formation--

The remedy for sulfite scaling is to keep the entering slurry pH at a level of 9 or less.[21] The actual critical level is not exactly known, and it varies with the type of scrubber. There are some limitations as to how much the return pH can be controlled. It should be noted that the elevation of pH in the reaction tank is due to addition of the makeup lime, a quantity that cannot be varied very much if it is desired to keep the addition near the stoichiometric amount. The actual pH depends on such factors as: SO_2 content of the inlet gas, L/G ratio, delay time in the reaction tank, and absorbent feed ratio.

Sulfite oxidation to sulfate can be reduced by covering the reaction tank, reducing the flue gas oxygen content, and reducing the delay time in the reaction tank. Calcium sulfate scaling can be minimized by circulating calcium sulfate seed crystals, which act as nucleation sites forming homogeneous precipitation of calcium sulfate. Sufficient seed crystal concentration should be maintained by controlling the percent solids content of the slurry circulated within the system. The larger the surface area of the preexisting crystals, the more the chance of precipitation occurring on the crystals rather than on the scrubber system internals.

At the lime scrubbing installations in the United States, practice has varied widely in regard to sulfate crystal concentration. In some cases, where the fly ash makes up part of the total solids, the upper limit for solids is usually considered to be about 15 percent because of the increasing viscosity at higher levels.

For scale prevention, scale inhibiting agents have been used with some success. A study was conducted by Nalco Chemical Company for Southern California Edison, regarding scale inhibitors.[22] The most effective scale inhibiting agent was an organic polymer consisting of 52 percent polyolester and 48 percent polyamide dispersant (acrylonitrile), at a 300-ppm dosage level. Other organic polymers including sodium lignosulfonate were much less effective. It should be noted that the use of scale-inhibiting agents tends to reduce the effectiveness of flocculant materials required in some cases for the proper operation of thickeners.

The principle involved in this is that some organic compounds attach themselves to the surface of calcium sulfate lattices and prevent the bonding between crystals of calcium sulfate. The combined actions of various factors mentioned earlier have not been fully understood to the extent that the beneficial effects of scale-inhibiting agents can be predicted.

4.6.5.4 Effects of Various Factors on Scaling--

For scrubber/absorber design it is very important to understand the effects of various factors on scaling. These factors are discussed below.

1. Recycle of gypsum ($CaSO_4 \cdot 2H_2O$) crystals. Sulfate scaling can be minimized by circulating gypsum seed crystals up to about 5 percent by weight. The larger the surface area of the preexisting crystals, the lower the scaling will be on the scrubber intervals. As mentioned earlier, the total solids content should be approximately 10 to 15 percent.

2. pH: Sulfite scaling can be suppressed by keeping the pH of the slurry returned to the scrubber to 9 or less. The actual pH is dependent on other variables. Hence, there are some limitations as to how much the return pH can be controlled.

3. Degree of oxidation: Sulfate scale is formed in the system because of oxidation of calcium sulfite in the scrubber, reaction tank, and thickener. Therefore, the lower the oxidation of the sulfite scale, the less chance of scaling.

4. Degree of loop closing: For the definition of closed-loop operation, refer to the Material Balance section in this book. Addition of fresh water reduces the scaling potential.

5. L/G: The higher the L/G ratio, the lower will be the scaling potential. The L/G ratio is dependent on the type of scrubber. However, use of high L/G is a good way to reduce scaling and achieve high SO_2 removal efficiency. These advantages have to be weighed against higher pumping costs and the possibility of flooding at high L/G ratios.

6. Residence time in reaction tank: The solution leaving the slurry is supersaturated with gypsum even at high L/G and solids content. Thus, residence time in the reaction tank should be high enough for the supersaturation to dissipate, otherwise the sulfate-rich slurry will pass the critical supersaturation level, beyond which scaling will occur when it is recycled to the absorber.

7. Presence of cations such as Mg^{++} and Na^{+}: The presence of high levels of soluble cations such as Mg^{++}, Na^{+}, and K^{+} in the scrubber slurry reduces the quantities of $SO_3^{=}$ and $SO_4^{=}$ available for scale formation. Significant amounts of soluble cations can be introduced into the system with the reagents or fly ash. Magnesium in particular is of special interest because it reduces calcium sulfate supersaturation (by forming soluble neutral complexes with sulfate ion) and also promotes SO_2 removal.

4.6.6 Process Design Variables

Several of the primary process design variables that will affect SO_2 removal capability of the absorber are discussed. This is not to imply only these factors will control the absorption of SO_2; however, these are major design items in most installations.

4.6.6.1 Stoichiometry--

Stoichiometry is defined as the number of moles of lime required to react with 1 mole of SO_2. Theoretically, 1 mole of CaO will be required to produce 1 mole of $Ca(OH)_2$, which in turn will remove 1 mole of SO_2. Thus, the stoichiometry of lime FGD systems is 1 mole of CaO/mole SO_2 removed. The actual lime consumption for most lime-based FGD units is 1.05 to 1.30 mole of lime per mole of SO_2 removed. The higher the lime consumption, the higher the operating cost, because more usable lime may be lost. A number of Japanese units report lime consumptions below 1.0, and it is believed that the Japanese designs use less excess of lime.

If more restrictive regulations were required for an existing unit, there are two ways in which somewhat higher SO_2 removals could be obtained: by means of a higher lime consumption, and/or by using higher L/G ratio. This approach, which can give only marginal improvement, depends on the inherent design of the system with respect to the flexibility of available equipment.

4.6.6.2 L/G Ratio--

The ratio of lime slurry flow in the absorber to the flue gas flow, expressed in gal/1000 acf, is termed L/G. For a given set of system variables, there is a minimum value of L/G that is required to achieve the desired SO_2 absorption. The minimum L/G can be computed from equilibrium relationships. In practice, the FGD system must operate with an L/G value more than the minimum since equilibrium conditions are never achieved.

In moving bed absorbers the upper limit on the value of L/G is set by the flooding condition, which is an L/G of approximately 80 gal/1000 acf. Spray towers do not have flooding problems. However, the power required for pump operation is the constraint. Normal L/G values vary from 30 to 50 gal/1000 acf for moving bed absorbers, and from 60 to 80 gal/1000 acf for spray towers.

The gas velocity through the absorber should allow a certain residence time for the gas stream. In U.S. FGD systems, this ranges from 3 to 9 seconds. This factor should be considered when computing the operating L/G. Other major variables that have an impact on gas-liquid interface conditions are the type, size, and total height of the packings used to induce turbulence in the moving bed absorbers.

4.6.6.3 pH--

As the lime slurry enters the SO_2 absorber, the pH often ranges from 7.5 to 8.5. When the absorbent reacts with the SO_2, the pH of the slurry becomes more acidic. The pH of the slurry as it exits the absorber may range from 4.5 to 6.0.

Johnson[6] discovered in 1935 that the equilibrium vapor pressure of SO_2 over lime slurry is inversely proportional to the slurry pH, resulting in a lower SO_2 equilibrium vapor pressure at a higher (more alkaline) pH. Test work recently conducted at TVA's Shawnee test facility[23] demonstrated greater SO_2 removal at higher slurry pH with constant L/G ratios. The limitation to this approach is that the excess lime required for this operating mode increases the cost of operation, and the tendency toward scale formation.

The pH used as the desired absorbent slurry control point depends on the L/G ratio in the absorber, the inlet SO_2 concentration, and the required SO_2 removal. In general, however, a pH range of 8.0 to 8.5 may be expected.

As the absorbent is utilized, the pH of the slurry is affected by the conversion of calcium hydroxide to calcium sulfite/sulfate. The absorption of SO_2 makes the resulting slurry pH less alkaline. As noted, the exiting slurry pH may range from 4.5 to 6.0. As the pH of the slurry becomes more acidic, the SO_2 absorbing properties of the lime slurry are reduced. Therefore it may be seen that, as the SO_2-rich flue gas contacts the lime slurry, the rate of SO_2 absorption increases as the flue gas stream encounters more fresh absorbent.

Early lime FGD systems operated in the supersaturation range of calcium sulfate without there being any awareness of the necessity of controlling this variable. When massive deposits of hard sulfate scale and also some softer sulfite scale were discovered, steps were taken to learn to control this problem. One of the four basic mechanisms of scale formation is pH excursion. Scale formation problems have been less pronounced with lime absorbent systems, when compared with limestone absorbent systems, because the pH is often maintained at a higher (more alkaline) level.

The degree of calcium sulfite oxidation to calcium sulfate is reportedly reduced when the pH level is increased. The tendency to form high levels of dissolved calcium and sulfate ions in the slurry is thus suppressed using lime reagent at higher pH control levels. Whenever a pH control excursion occurs, and the pH of the absorber slurry drops below 4.0 to 4.5, regardless of the type of reagent (lime or limestone), severe and rapid formation of calcium sulfate scale can occur.

As scale forms in the absorber, concentration gradients and/or differential aeration cells are established between the particles trapped beneath the deposit and those outside. The natural corrosive characteristics of the more acidic calcium sulfite and sulfate tend to attack the absorber exposed surface. The combination of the natural corrosiveness of the medium and the concentration cells resulted in severe corrosion of early installations.

4.6.6.4 Increased Gas Velocity--

The most common flue gas velocities encountered in absorber design range from 7 to 10 ft/s. The EPRI is currently testing a cocurrent scrubber at the Shawnee test facility. Gas velocity up to 30 ft/s will be tested. Tray towers often are in the range of 7 to 8 ft/s, and the velocity in TCA, spray tower, and venturi absorbers most often ranges from 8 to 10 ft/s.

4.6.6.5 Liquid Distribution--

For best SO_2 absorption, the intimate contact between the SO_2 molecules in the flue gas and the droplets of lime-based absorbent is critical. The smaller the droplet of absorbent slurry, the better the contact and the absorption. To achieve this contact in spray towers, finer spray nozzles are employed. In some cases, high pressure pumps are used to obtain finer atomization of the slurry. In other cases, impinger plates are used to physically reduce the size of droplets exiting the nozzle. In a venturi, the pressure drop across its throat causes the liquid droplet to break up into many finer droplets. The venturi principle is also used in packed- and moving-bed absorbers. As the gas flow is forced between the spheres in the bed, many small venturi effects occur. The wetted sides of the spheres serve as an area of mass transfer.

In a spray tower, the droplet size must be controlled by nozzle type, line pressure, and use of impinger plates. In a mobile-bed absorber, the size droplet is not so critical since the action of the gas flowing up through the packing or balls causes the breakdown of the droplet size.

4.6.6.6 Water Balance--

Three external factors will impact the water balance of an FGD system: the ambient humidity, the rainfall of the area, and the climate. These three items will determine how the water lost in the adiabatic cooling of the flue gas is replaced to maintain a closed system. For greater detail of water balance please read EPRI report[24] FP 627 entitled "Lime/Limestone Scrubber Operation and Control Study."

As the gas stream is cooled, water is absorbed by the gas. This is the primary point of water loss throughout the FGD system.

When one considers individual FGD plant sites from a design standpoint, specific climatic conditions should be included to avoid unanticipated problems that might have a major impact on operations. The average temperature, wind velocity, precipitation, and other items should be considered to determine their possible effects on the system-wide water balance.

The quantity of the water used at the various points throughout the FGD system is an important consideration. It is desirable that the FGD system operate in the closed-loop mode, i.e., makeup water should not exceed that lost in the flue gas and the sludge. Some major uses of water in FGD systems are as follows:

1. For wet particulate scrubber makeup
2. For slaking of lime
3. For dilution of the lime slurry and/or additional makeup for the SO_2 absorber

4. As mist eliminator wash

5. As pump seal water

All five of these use points may impact the scrubber/absorber operation. All the above uses are quantified for six specific scrubbers in EPRI report[25] FP 627 entitled "Lime/Limestone Scrubber Operation and Control Study."

Water used in the wet particulate scrubber is not required to be of the best quality. Often recycled water from the sludge pond is used.

The water required for slaking the lime is much more critical. It is desirable to use water of (or near) potable quality. Waste or recycle process waters containing sulfites and sulfates retard the slaking process--not only is more time needed to complete the slaking step, but the quality of the resulting lime slurry is impaired. The lime particle size increases and the surface area shrinks, which in turn retards. In fact, some of the lime does not hydrate at all and is wasted. The only explanation is that the lime precipitates the SO_3 and SO_4 ions as calcium sulfite-sulfate, which coats the unreacted CaO particles and prevents complete water penetration into the lime particles.

Once the lime has been slaked, however, recycled or waste process water can be used to dilute the thick lime slurry to the desired consistency. There is little or no effect by the SO_3 and SO_4 ions on the quality of the diluted lime slurry produced. The chloride ion in dilution water in reasonable amounts appears at present to exert a minimal deleterious effect on the resulting slurry.

Mist eliminator wash may be freshwater, recycled water, or any combination of fresh and recycled water. Ideally, all freshwater would be used; however, to attain closed-loop operation, a mix is frequently required. Continuous wash is often accomplished using recycled water. Freshwater normally is used for high volume, intermittent wash. Since the trend in construction of mist eliminators is toward the zigzag baffle or the continuous chevron type of mist eliminator made of plastic materials, and because the mist eliminators are largely corrosion resistant, the chemical makeup of the water normally has little effect except for the possible buildup of scale when sulfate saturated water is used.

Pump seal water is most often fresh water. Concern about the chemical constituents, suspended solids, and sulfate saturation of the recycled pond water dictates that recycled water be used only with great caution. A major concern is that in the presence of the heat associated with pump operation, the sulfate and other solids in the recycled pond water would deposit and cause pump failure.

The sources of makeup water are as follows:

1. Freshwater
2. Sludge pond recycle water
3. Wastewater from other plant processes
4. Cooling tower blowdown

The nature of the cooling tower chemical treatment, impurities that may become concentrated in the feed water stream, and particulates that may be washed from the air by cooling tower flow, all must be considered in the decision as to whether to utilize this water stream.

4.6.6.7 Interfacial Area--

The interfacial area may be defined as that area in which the absorbent slurry contacts the flue gas stream. This will be affected by the L/G ratio, the gas velocity, the slurry droplet size, liquid distribution, and the type of absorber. An adequate contact area is required for the desired SO_2 removal from the flue gas stream. The impacts of the L/G ratio, the gas velocity, and the liquid distribution have been discussed as they affect SO_2 removal design for an absorber.

In a TCA, the size of balls or marbles used and the depth of the contact bed are the two critical items. In a spray tower, the height (length) of the tower, droplet size, nozzle pressure drop, spacing of sprays, and coalescence of droplets are the critical design points. The height, at a given gas velocity, gives the residence or contact time when SO_2 may be removed from the gas stream. Internal sources of gas turbulence such as grids must be considered in absorber design.

4.6.7 Existing Facilities

Table 4.6-12 indicates the operating experience of existing lime FGD systems in terms of months of operation. A summary of the performance of these systems is presented below.

4.6.7.1 Louisville Gas and Electric, Cane Run Unit 4[26]--

Following startup of Cane Run Unit 4, 75 to 80 percent of the SO_2 was removed at full load. To increase the SO_2 removal, a new spray header system was installed above the mobile bed sprayer to improve the L/G ratio. This resulted in superior contact and an SO_2 removal rate above 85 percent. The spray nozzles were changed from plastic to ceramic to resist cracking caused by expansion. The scrubber is now running consistently above 90 percent SO_2 removal. This system has never experienced scaling or plugging problems.

Table 4.6-12. SUMMARY OF OPERATING LIME FGD SYSTEMS AS OF JANUARY 1978

Utility name	Process/generating units	FGD/MW	Startup	Experience, mo
	Lime scrubbing			
Pennsylvania Power	Bruce Mansfield No. 1	825	4-76	21
Pennsylvania Power	Bruce Mansfield No. 2	825	7-77	6
Louisville Gas & Electric	Cane Run No. 4	178	8-76	17
Columbus & Southern	Conesville No. 5	400	1-77	12
Duquesne Light	Elrama Power Station	510	10-75	27
Kentucky Utilities	Green River Nos. 1, 2, and 3	64	9-75	28
Kansas City Power & Light	Hawthorn No. 3	140	11-72	62
Kansas City Power & Light	Hawthorn No. 4	100	8-72	65
Louisville Gas & Electric	Paddy's Run No. 6	65	4-73	57
Duquesne Light	Phillips Power Station	410	7-73	54
		3517		349
	Lime/alkaline fly-ash scrubbing			
Montana Power	Colstrip No. 1	360	11-75	26
Montana Power	Colstrip No. 2	360	7-76	18
Minnkota Power Co-Op.	Milton R. Young No. 2	450	9-77	4
		1170		48
	Lime/limestone scrubbing			
TVA	Shawnee No. 10A	10	4-72	69
TVA	Shawnee No. 10B	10		69
		20		138

4.6.7.2 Louisville Gas & Electric, Paddy's Run Unit 6[27]--

Initial startup of Paddy's Run Unit 6 took place on April 5, 1973. A 7-hour shutdown was required when a marble bed support plate broke, and the malfunction and repair of the dual strainer switch in the bottom of the scrubber module caused two more outages. During the beginning of 1976, the scrubber achieved 99 percent SO_2 removal. Tests run using calcitic lime, instead of the usual carbide lime, resulted in scaling from the increased oxidation level of the calcitic lime. When magnesium hydroxide [$Mg(OH)_2$] was added to the lime, this problem was eliminated.

4.6.7.3 Kentucky Utilities, Green River Power Station[28,29]--

Serious plugging problems were observed at Green River following startup on September 13, 1975. Hard gypsum scale plugged the lower mobile beds, and the spray nozzles also experienced plugging problems. To remedy this, the oxygen content of the flue gas was reduced by minimizing air leakage into the system. Thus, the oxidation of sulfite to sulfate was prevented, and the pH was lowered enough to prevent the precipitation of gypsum. The scrubber balls were also replaced with larger ones to reduce migration. To eliminate pitting that occurred behind the Carboline stack liner, the liner was replaced with Precrete G-8 and metal backup plates were welded to the pitted portions of the stack.

4.6.7.4 Duquesne Light, Phillips[27,30,31]--

Partial startup at Phillips station occurred July 1973, and full startup took place on March 17, 1975. High calcium lime caused deposit buildup around the throat dampers and lower cone; deposits also formed in and around the spray nozzles. This problem was partially alleviated by closing alternate nozzles, thus producing higher velocities in the other nozzles. Tests indicated that using lime with higher MgO content also reduced the accumulation of scale. In one test the use of 8 to 10 percent MgO lime almost totally eliminated deposits and resulted in an increased SO_2 removal rate of 83 percent. During September 1977, when the system was running at higher capacity, the SO_2 removal rate dropped to 50 percent.

4.6.7.5 Duquesne Light Elrama[27]--

The main problem encountered following startup at the Elrama station was a poor SO_2 removal rate. In addition, there were problems with a bleed valve leak. Dravo Thiosorbic lime is now used, as it is at Phillips station, for increased SO_2 removal.

4.6.7.6 Columbus and Southern Ohio Electric, Conesville Unit 5[27]--

Because the lining of scrubbing Unit 5A was destroyed by fire prior to startup at Conesville Unit 5, the scrubber had to be relined before it was put into service. Scrubbing Unit 5B started operating on February 13, 1977, using Dravo Thiosorbic lime with an MgO content of 3 to 8 percent.

Problems encountered were a carryover of scrubbing liquid into the mist eliminator and poor velocity distribution through TCA beds. When the flow rate was low, some plugging occurred. Scaling and buildup of deposits inside the scrubbers continue to be a problem.

4.6.7.7 Pennsylvania Power, Bruce Mansfield Units 1 and 2[27,32,33]--

Both systems at Bruce Mansfield have experienced problems with corrosion, scale, and stack liner failures. It was hoped both systems could remove the required amount of SO_2 using five of the six scrubbing trains, but all six were needed because the flue gas flow was greater than expected. Scale formation, plugging, and acid corrosion resulted when the pH of the recirculating slurry was controlled manually (because of poor automatic pH control). When the pH monitors were relocated, however, this problem was eliminated.

REFERENCES

1. Treybal, R.E., Mass Transfer Operations, 2nd ed. McGraw-Hill, New York, 1968.

2. Perry, R.H., and C.H. Chillon. Chemical Engineer's Handbook, 5th ed. McGraw-Hill, New York, 1978.

3. Crow, G.L. Corrosion Tests Conducted in Prototype Scrubber Systems. In: Corrosion Problems in Air Pollution Control Equipment Symposium, Atlanta, 1978.

4. Kopecki, E.S., and C.E. McDaniel. Corrosion Minimized/ Efficiency Enhanced in Wet Limestone Scrubbing, Power Eng. 80, No. 4, April 1976.

5. Corrosion Properties of an SO_2-Wet-Limestone Scrubbing System. International Corporation Forum, Toronto, Canada, April 1975.

6. Atlas Minerals and Chemicals Division Glass Flake Systems Bulletins 4-1100, 4-1200, 4-1300, and 4-1400; Fabric Reinforced Systems Bulletins 4-2100, 4-2200, 4-2300, and 4-2400.

7. Lewis, E.C., M.P. Stengel, and P.G. Maurin. Performance of TP-316L SS and Other Materials in Electric Utility Flue Gas Wet Scrubbers. In: Corrosion Problems in Air Pollution Control Equipment Symposium, Atlanta, 1978.

8. Corrosioneering, Inc. Specifications/Information Corrosion Resistant Linings and Coatings. B-100.

9. Heil Process Equipment Company. Regiline Corrosion-Resistant Coatings and Linings for the Power Industry, BM-403.

10. Dudick Corrosion Proof, Inc. Application Guide, Tech Data Sheets.

11. Johnson, R.S., Jr. Materials Performance in a Flue Gas Particulate and Desulfurization System. In: Corrosion Problems in Air Pollution Control Equipment Symposium, Atlanta, 1978.

12. Boova, A.A. Chemical Resistant Masonary, Flake and Fabric Reinforced Linings for Pollution Control Equipment. In: Corrosion Problems in Air Pollution Control Equipment Symposium, Atlanta, 1978.

13. Singleton, W.T., Jr. Protective Coatings Formulated From Vinyl Ester Resins for the Air Pollution Control Industry. In: Corrosion problems in Air Pollution Control Equipment Symposium, Atlanta, 1978.

14. Fontana, M.G., and N.D. Greene. Corrosion Engineering. McGraw-Hill Book Company, New York, 1967. pp. 157-193.

15. Private communication with R. Vanness, Louisville Gas and Electric, February 1978.

16. Laseke, B., Jr. EPA Utility FGD Survey, December 1977 to January 1978, and April to May 1978 update.

17. Private communication with J. Beard and V. Anderson, Kentucky Utilities, February 1978.

18. Private communication with D. Boston, Columbus and Southern Ohio Electric, February 1978.

19. Private communication with R. O'Hara and J. Mahone, Duquesne Light Company, February 1978.

20. Gogineni, M.R., and P.A. Maurin. Sulfur Oxides Removal by Wet Scrubbing - Application to Utility Boilers. Presented at Frontiers of Power Technology Conference, Stillwater, Oklahoma, October 1-2, 1975.

21. Uchida S., C.Y. Wen, and W.J. McMichael. Role of Holding Tank in Lime and Limestone Slurry Sulfur Dioxide Scrubbing. Ind. Eng. Chem., Process Des. Dev., Vol. 15, No. 1, 1976.

22. Shah, I.S. Paper Presented at Second International Symposium for Lime/Limestone Wet Scrubbing, New Orleans, La., November 8-12, 1971, (Proceedings issued by EPA, APTD-1161, 1, 345.)

23. Borgwardt, R.H. Pilot studies related to Unsaturated Operation of Lime and Limestone Scrubbers. Presented at Symposium on Flue Gas Desulfurization - Atlanta, November 1974. (Proceedings issued by EPA, EPA-650/2-74-126-a.)

24. Lime/Limestone Scrubber Operation and Control Study. EPRI report FP 627.

25. EPRI report on water balance for 6 systems.

26. Van Ness, R.P. Louisville Gas and Electric Company Scrubber Experiences and Plans. Paper presented at FGD Symposium, Hollywood, Florida, November 8-11, 1977.

27. Laseke, B.A., Environmental Protection Agency Utility FGD Survey: December 1977 - January 1978. EPA-600/7-78-051a. March 1975.

28. Beard, J.B. Scrubber Experience at the Kentucky Utilities Company Green River Power Station. Paper presented at FGD Symposium, Hollywood, Florida, November 8-11, 1977.

29. Laseke, B.A. Survey of Flue Gas Desulfurization Systems: Green River Station, Kentucky Utilities. EPA-600/7-78-048e. March 1978.

30. Nelson, R.L., and R.E. O'Hara. Operating Experiences at the Phillips and Elrama Flue Gas Desulfurization Facilities. Paper presented at the Second Pacific Chemical Engineering Congress, Denver, August 28-31, 1977.

31. Knight, R.G., and S.L. Pernick. Duquesne Light Company Elrama and Phillips Power Stations Lime Scrubbing Facilities. Paper presented at the FGD Symposium, New Orleans, March 1976.

32. Laseke, B.A. Survey of Flue Gas Desulfurization Systems: Bruce Mansfield Station Pennsylvania Power Company (Draft). EPA-68-02-2603.

33. Private communication with R. Forsythe and W. Norrocks, Pennsylvania Power Company, February 1978.

CONTENTS

4.7 MIST ELIMINATORS

Page

4.7.1 Introduction 4.7-1

4.7.2 Description and Function 4.7-1

4.7.3 Types of Mist Eliminator 4.7-3

- 4.7.3.1 Continuous or Discontinuous Chevron Baffle 4.7-3
- 4.7.3.2 Chevron Mist Eliminator Design and Performance 4.7-3
- 4.7.3.3 Radial Vane 4.7-10

4.7.4 Mist Eliminator Design Factors 4.7-13

- 4.7.4.1 Mist Eliminator Shape 4.7-13
- 4.7.4.2 Number of Passes 4.7-14
- 4.7.4.3 Spacing Between Vanes 4.7-14
- 4.7.4.4 Slanted Mist Eliminator 4.7-14
- 4.7.4.5 Materials of Construction 4.7-18
- 4.7.4.6 Special Drainage Devices 4.7-18

4.7.5 Mist Eliminator Equipment Design Considerations 4.7-18

- 4.7.5.1 Mist Eliminator Configuration (Horizontal vs. Vertical Gas Flow) 4.7-20
- 4.7.5.2 Use of Bulk Separation, Wash Tray, and Knock-out Devices 4.7-22
- 4.7.5.3 Freeboard Distance 4.7-22
- 4.7.5.4 Number of Stages 4.7-26
- 4.7.5.5 Distance Between Stages 4.7-26
- 4.7.5.6 Passage Geometry 4.7-26
- 4.7.5.7 Miscellaneous 4.7-26

4.7.6 Mist Eliminator Wash System 4.7-27

- 4.7.6.1 Wash Water Type 4.7-27
- 4.7.6.2 Wash Direction 4.7-28
- 4.7.6.3 Wash Duration and Water Quantity 4.7-28
- 4.7.6.4 Wash Water Pressure 4.7-28

CONTENTS (continued)

4.7.7 General Factors 4.7-29

- 4.7.7.1 Mist Eliminator Pressure Drop 4.7-29
- 4.7.7.2 Overall Collection Efficiency 4.7-29
- 4.7.7.3 Mist Loading and Particle-size Distribution 4.7-30

4.7.8 Existing Facilities (Experience and Equipment Detail) 4.7-30

- 4.7.8.1 Phillips Station (Duquesne Light Company) 4.7-36
- 4.7.8.2 Paddy's Run 6 (Louisville Gas and Electric Company) 4.7-36
- 4.7.8.3 Elrama Station (Duquesne Light Company) 4.7-36
- 4.7.8.4 Green River Station (Kentucky Utilities) 4.7-36
- 4.7.8.5 Bruce Mansfield (Pennsylvania Power Company) 4.7-37
- 4.7.8.6 Conesville (Columbus and Southern Ohio Electric Company) 4.7-38
- 4.7.8.7 Cane Run (Louisville Gas and Electric Company) 4.7-38
- 4.7.8.8 Hawthorn (Kansas City Power and Light Company) 4.7-38
- 4.7.8.9 Colstrip (Montana Power Company) 4.7-38

4.7.9 Recommendations 4.7-38

References 4.7-40

4.7 MIST ELIMINATORS

4.7.1 Introduction

In any wet scrubbing system, small drops of liquid are formed and carried out of the scrubber with the gas. A well-designed mist elimination device is therefore necessary to prevent plume rain and mist entrainment that would cause corrosion and scaling of downstream equipment. In addition, if a gas reheater is required to evaporate the droplets, an efficient mist eliminator can substantially reduce the reheating cost by minimizing the amount of moisture that must be evaporated before a temperature rise in the flue gas is obtained.

4.7.2 Description and Function

A mist eliminator is defined in Guidelines for the Design of Mist Eliminators for Lime/Limestone Scrubbing Systems[1] as: "A device employed to collect, remove, and return to the scrubbing liquor the slurry droplets entrained with the desulfurized flue gas exiting the scrubber or absorber."

The most common device is a set of baffles or slats set in such a way as to impart a zigzag flow to the gas over distances ranging from a few inches to a foot. Mist drops are removed by impaction on surfaces that change the direction of gas flow. Cyclonic flow, which causes the entrained moisture to impact on ductwork surfaces, is also effective in mist removal.

The mist drops generally contain both suspended and dissolved solids. The suspended solids are derived from particulates collected by the scrubber, lime particles introduced into the scrubbing liquid, and/or products of chemical reactions occurring within the scrubber. Similarly, dissolved solids come from impurities in the gas, lime introduced into the scrubber liquid, and/or products of reaction.

Mist carryover can cause a variety of problems, both within the air pollution control system and in the ambient atmosphere. In cases where an induced-draft fan is used, drops can collect in the fan. These drops tend to deposit solids causing failure of the blades, housing, or supporting structures as a result of excessive vibration or corrosion problems. Solids can also be deposited in the reheater, ductwork, and stack; and as was the case at Bruce Mansfield (Pennsylvania Power), the deposits can break off in chunks and be blown out of the stack. Reheater plugging and corrosion is a very common experience at lime scrubbing installations, and problems with the reheaters can usually be traced directly to inefficient mist eliminators. Measures taken to reduce reheater plugging include use of efficient mist eliminators upstream of the reheaters and use of soot blowers in the reheater housing. Entrained mist drops that reach the stack can cause problems in the surrounding area as a result of "rainout" of liquid drops.

The major mist eliminator problems encountered in lime scrubber applications are plugging, scaling, and reentrainment/carryover problems in downstream equipment. A soft, mudlike deposit and/or scale can accumulate on the mist eliminator in the course of time, unless it is sufficiently sprayed with wash water of reliable quality. If solids build up to the point where the collector is completely blocked and "blow holes" develop, the result will be increased pressure drop across the mist eliminator, increased wear and erosion in the blow-hole areas, and drastic reduction in overall efficiency.

Solid deposits of calcium sulfite and unreacted lime can occur in lime systems when the solid carryover from the scrubber is trapped in the mist eliminator. More serious, however, is formation of sulfate scale, which results from oxidation of the sulfite solution collected on the mist eliminators. Scaling can also occur as the result of absorption of residual flue gas SO_2 by the unreacted lime on wetted surfaces. High stoichiometric ratios of lime (poor lime utilization) compound the SO_2 absorption problem, since larger quantities of unreacted lime are then carried over to the mist eliminator. Surface irregularities formed by the crystalline scale increase the potential for mud accumulation and decrease the effectiveness of washing operations.

The failure of mechanical parts is another cause of breakdown. In some cases collector blades, especially fiberglass ones, can in time become embrittled. Entrained solids combined with forces of high-pressure wash-water sprays can deform, shatter, or break the blades. Partial plugging of the mist eliminator can also increase pressure drop, which in turn sometimes causes the blades to collapse. In early systems, stress corrosion cracking occurred in mist eliminators constructed from 316L stainless steel. Newer systems, such as the now-terminated Mohave unit, use Incoloy 825.

In installations where the scrubber exit gas is reheated, a high-efficiency mist eliminator is a very important part of the scrubbing system. The reheat energy requirement increases as mist carryover increases. Increasing mist carryover also leads to the collection of entrained substances on the heat exchange surfaces of the reheater, eventually causing plugging and/or corrosion. A high-efficiency mist eliminator is also important, however, even when the gas is not reheated. It is usually required to eliminate mist carryover through the stack.

4.7.3 Types of Mist Eliminator

A number of designs are available to remove liquid and solid particulates from gas streams, including the wire mesh, tube bank, gull wing, and electrostatic precipitator (ESP) types. For lime scrubbing operations, however, the two most relatively successful designs in use are the chevron baffle and the radial vane. These two types alone are discussed in this report.

4.7.3.1 Continuous or Discontinuous Chevron Baffle--

The chevron baffle can consist of either continuous or discontinuous zigzag baffles (Figure 4.7-1). The baffle uses the inertial impaction collection mechanism, whereby the gas stream with its entrained liquid droplets is forced to make abrupt changes in direction. When the stream changes direction, droplets impinge on the baffle walls, coalesce, and drain from the mist eliminator blade (Figure 4.7-2). In Figure 4.7-2(a) the chevron is positioned horizontally (vertical gas flow); hence drops fall as shown into the scrubbing system. If the chevron were positioned vertically (horizontal gas flow), drops would fall vertically along the mist eliminator (Figure 4.7-2(b)). This configuration allows wash water to be easily isolated from the scrubber system.

Although the chevron mist eliminator is simple, its collection efficiency when dealing with moderate to large droplets is excellent. Its low pressure drop and wide-open construction make it a popular choice in lime scrubbing operations, where the high solids content of the slurry would readily cause plugging in other eliminator types.

4.7.3.2 Chevron Mist Eliminator Design and Performance--

Heil chevron mist eliminator[2,3]--The Heil design is shown in Figure 4.7-3 (vertical configuration); its removal efficiency curve is shown in Figure 4.7-4. There are no holes in the blades for mounting in a Heil assembly and consequently bypass leaks through hole clearances are avoided. Heil blades can be used in the vertical or horizontal position. Their assemblies and modules come in standard sizes, but can also be custom fabricated.

Matsuzaka mist eliminator (Japan)[4]--The Matsuzaka Co. manufactures and markets the Humboldt Wedag "Lamellar" separator (Figure 4.7-5). Because of its higher cost, it can compete with conventional chevron baffles only when superior performance is required (for droplets of less than 30 μm). One of its advantages over chevrons is that maldistribution of gas has a much less adverse effect on collection efficiency because its troughs prevent reentrainment when installed at an angle or in a horizontal duct, even if a disproportionately large amount of mist

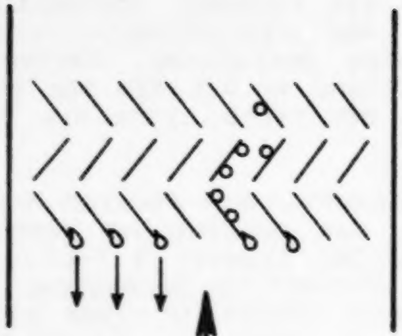

GAS DIRECTION

Figure 4.7-1(a). Discontinuous horizontal chevron zigzag baffle.

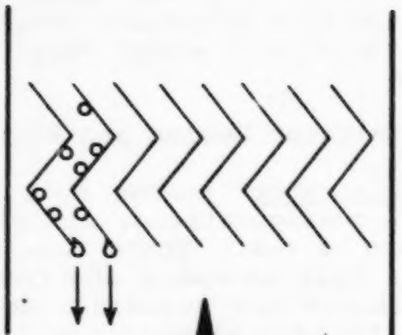
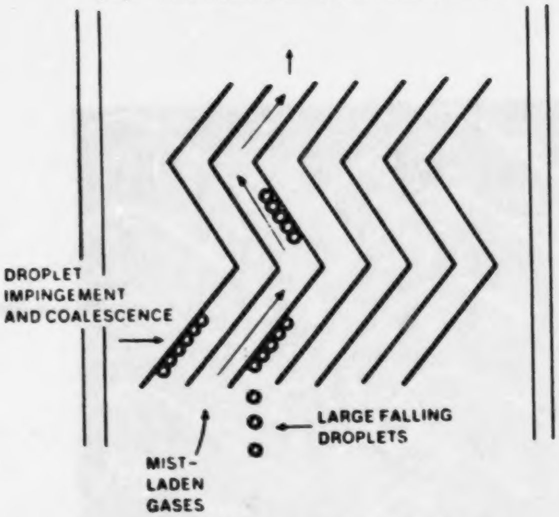

GAS DIRECTION

Figure 4.7-1(b). Continuous horizontal chevron zigzag baffle.

(a) HORIZONTAL CONFIGURATION


DROPLET IMPINGEMENT AND COALESCENCE
LARGE FALLING DROPLETS
MIST-LADEN GASES

(b) VERTICAL CONFIGURATION

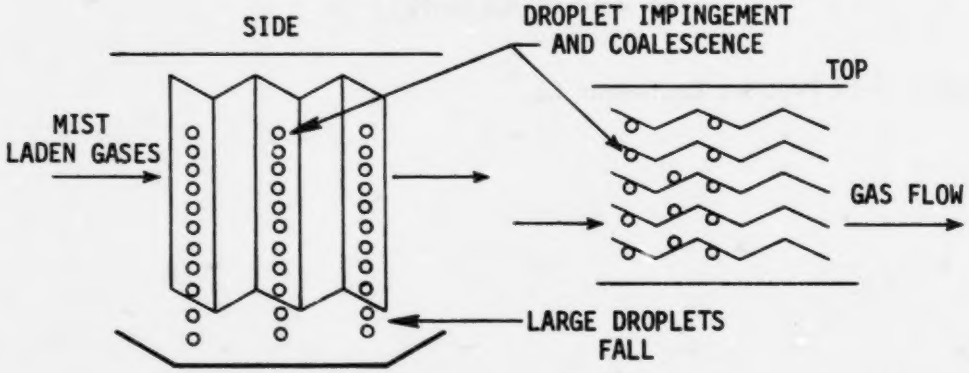

SIDE
DROPLET IMPINGEMENT AND COALESCENCE
TOP
MIST LADEN GASES
GAS FLOW
LARGE DROPLETS FALL

Figure 4.7-2. The chevron impingement principle.[3]

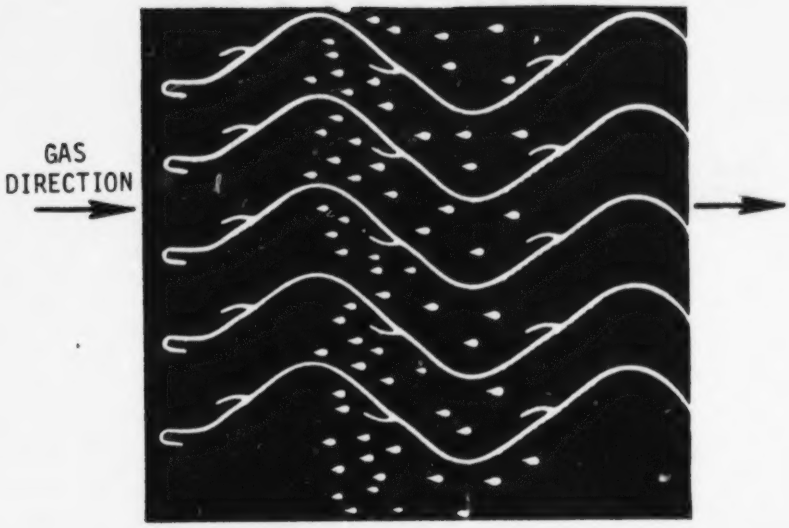

GAS
DIRECTION

Figure 4.7-3. Heil chevron mist eliminator.[2]
(Top view of ductwork)

Courtesy: Heil Process Equipment Co.

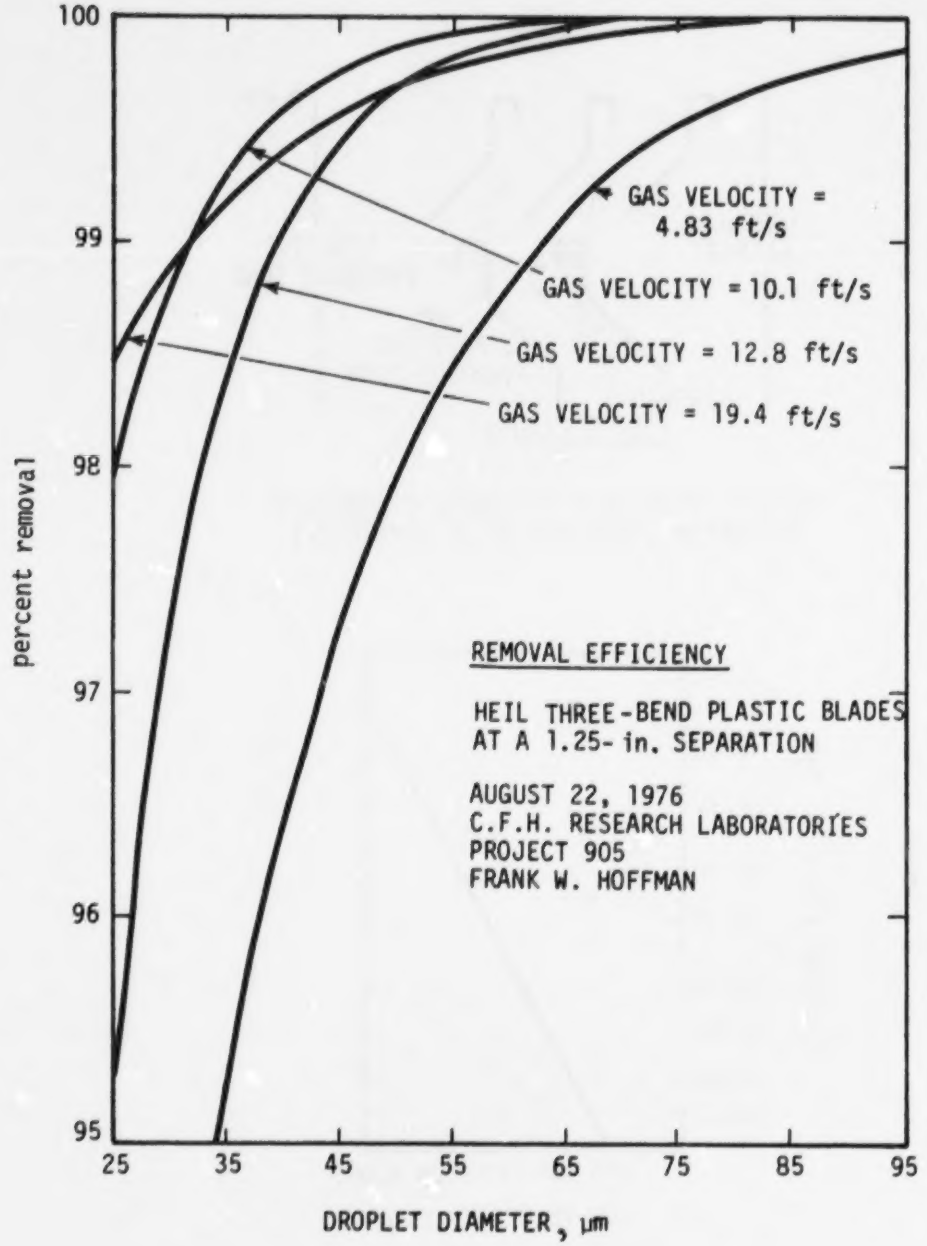
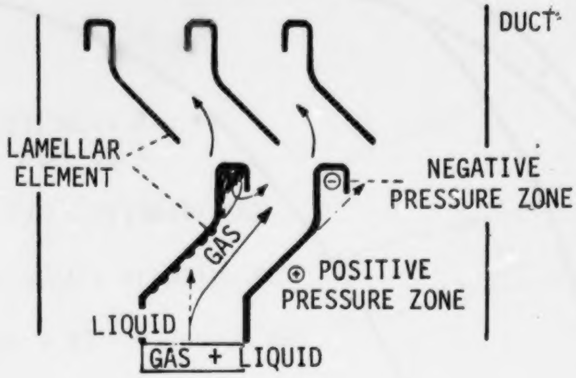


Figure 4.7-4. Heil chevron mist eliminator performance.[4]


DUCT
LAMELLAR ELEMENT
⊖
NEGATIVE PRESSURE ZONE
GAS
⊕ POSITIVE PRESSURE ZONE
LIQUID
GAS + LIQUID

WORKING PRINCIPLE OF HUMBOLDT LAMELLAR SEPARATOR (TRANSECTION OF SEPARATOR)

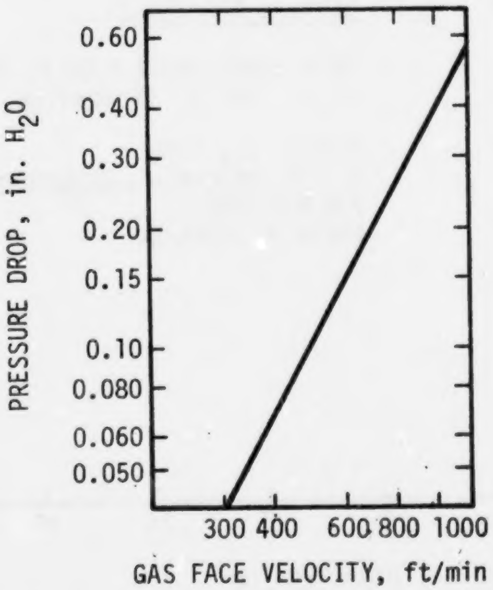


Figure 4.7-5. Vertical configuration of Humboldt Lamellar separator in horizontal duct (looking downward) marketed by Matsuzaka.[4]

is collected at one point on the cross section. For this reason, a design with a collection trough is more likely to perform as expected, since uniform gas distribution is seldom attained with any mist eliminator.

A main problem in lime scrubbing application is clogging at the bottom of the trough. In the early installations, the first row, or "bank," remained clear while the second one plugged. To alleviate this problem, the banks were separated and a spray installed between them. The baffles in the first bank were also set 2 in. apart instead of 1-1/4 in., and the troughs were made larger.

The present "standard" design consists of three banks with a continuous wash on the first, a 30-s intermittent wash on the second, and no wash on the third. Fresh water is used on the first bank, but recycled liquor can be used on the others. About two-thirds of the wash liquid is applied on the top of each bank. The vertical trough is mounted with a considerable slope, and a special spray nozzle keeps it clean.

The usual gas velocity is 23 ft/s; pressure drop through the three banks is approximately 2 in. H_2O. The expected performance is for 99 percent removal of the 15- to 20-μm drops.

NGK mist eliminator (Japan)--This design is licensed from Euroform (Aachen, Germany) and is similar to that offered by the Heil Company. The configuration is a shallow S-curve with relatively small "hooks" attached to the surfaces (similar to Figure 4.7-3).

The NGK eliminator has had trouble with deposits in the vertical "pocket" channels. The preferred nominal velocity range at the mist eliminator for lime scrubbing application is 19.5 to 26 ft/s. An NGK mist eliminator in the horizontal position (vertical gas flow) removes drops as small as 30 μm, and in the vertical position (horizontal gas flow) it removes drops down to 15 μm. In the vertical position, it can accept higher inlet loadings without reentrainment. Practically all units supplied by NGK are of the vertical type. The company puts considerable emphasis on turning vanes to achieve uniform gas distribution over the mist eliminator cross section. Pressure drop through the mist eliminator is approximately 1 in. H_2O. Its efficiency guarantee is usually based on outlet solids loading.

Munters Euroform mist eliminator[5]-- Various designs are available for this mist eliminator, which is made under license from NGK (Japan). The main difference between them is in blade spacing. The various models available include the T-8, T-271(K), T-271(M), T-71, TS-5/2, and T-100. Letters or numbers referring to these models do not have a specific meaning; however, each one has a particular characteristic and application.

Model T-8 is a coarse separator for vertical gas flow. Model T-271 is used in applications requiring fine droplet removal. It, too, is used with vertical gas flow. Letters "K" and "M" after T-271 indicate, respectively, plastic and metal materials of construction. Model T-71 is a half-sized version of T-271. Model TS-5/2 is employed with horizontal gas flow. Models in the T-100 series are made of various plastics. The "20" in Model No. T-120 indicates that it has 20-mm spacing. Similarly, T-125 has 25-mm spacing.

Figure 4.7-6 shows the configuration of a section and the pressure drop curve for the T-271 type. The wash procedure with this design involves a fresh water wash at the upper eliminator, with preceding washes using recycled liquor. In the case of the vertical flow eliminators, wash rates range from 0.5 to 0.75 gal/min per ft^2 of eliminator surface using a coarse, full-cone spray at 35 to 40 psi and for a period of 6 to 12 min/h. These rates prevent buildup on nozzles and surfaces. The wash water can be reused elsewhere in the process. This occurs only in horizontal gas flow mist eliminators where the drainage is collected.

Sprays are normally applied to both the upper and lower surfaces in the primary eliminator and can be used on the bottom face in the upper (secondary) eliminator. The T-8 is normally used for the primary, and the T-271 model for the secondary eliminator for use in scrubbing systems with vertical gas flow.

The highest efficiency eliminators are horizontal flow types and are used where overall design permits. The gas velocity through horizontal flow mist eliminators is higher. The same spray procedures are used, except that spray volumes are 1.5 to 2 gal/min per ft^2 at the rate of 1 to 3 min every 10 min. This increased spray rate is necessary because increased velocity and droplet removal efficiency of the eliminators would otherwise cause a noticeable drying effect and subsequent crusting.

4.7.3.3 Radial Vane[6]--

The radial vane is a cyclonic separator. One of the limitations of this type of mist eliminator is that it always has to be installed in a vertical duct. As shown in Figure 4.7-7, curved vanes redirect the gas stream from the vertical into a horizontal, spinning flow toward the vessel wall. Heavier liquid and solid particles in the mist are first accelerated (by the reduced cross-sectional area) and then directed to the vessel walls, where they are collected. The collected mist drains back into the scrubber, and cleaned gases exit to the stack. The primary collection mechanism is inertial impaction. Though considerably more expensive than the chevron mist

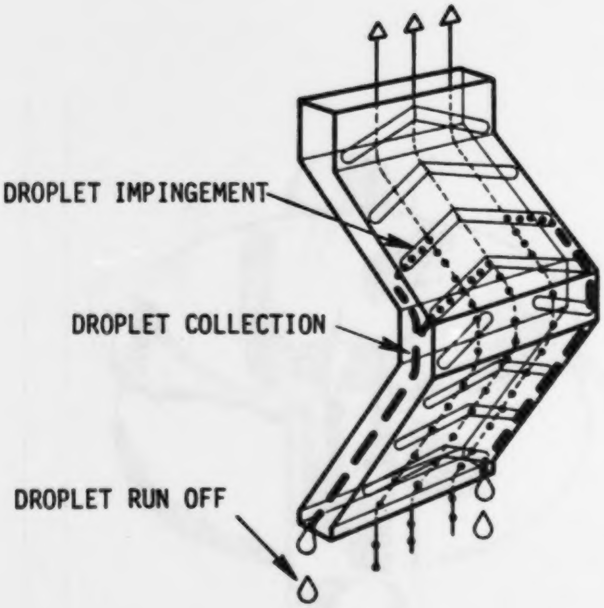

DROPLET IMPINGEMENT
DROPLET COLLECTION
DROPLET RUN OFF

Figure 4.7-6. Munters Euroform mist eliminator.[5]

Courtesy Munters Corp.

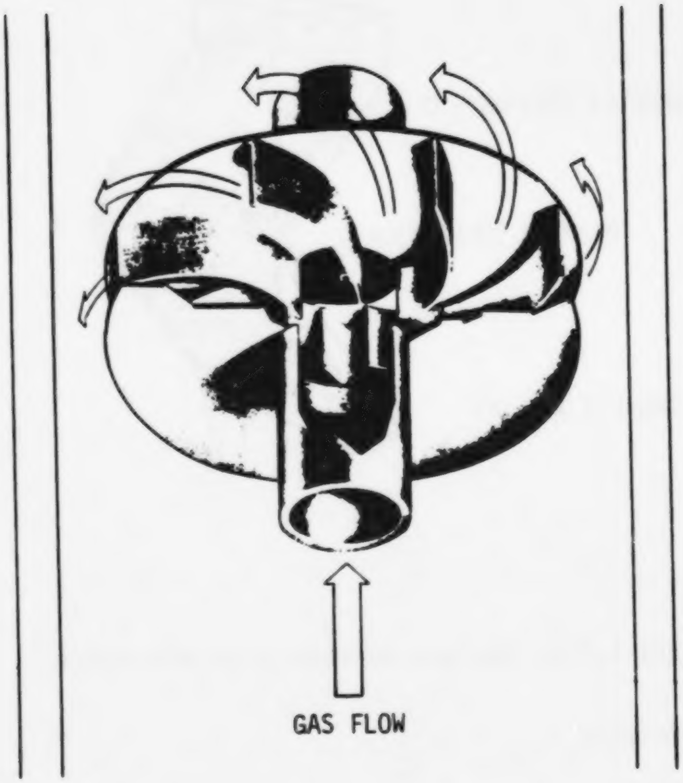


Figure 4.7-7. Radial-vane mist eliminator.[6]

Courtesy Koch Engineering Co.

eliminator in regard to both capital and operating costs, radial-vane devices are claimed to have far superior collection efficiency and greater washability. The pressure drop through the radial-vane mist eliminator is considerably higher compared with that of the chevron type; it ranges from 2 to 6 in. H_2O during operation. To reduce solids loading, the radial-vane eliminator in some designs is preceded by an impingement tray whose underside surface is washed continuously with fresh water. The mist eliminator itself, however, is not washed when the tray is used. The center and rim of the scrubber vessel are blocked out to increase the gas velocity. It should be noted that only two radial-vane mist eliminators have been installed on utility scrubbers, but they have not operated successfully (See Section 4.7.8) and are being replaced with chevrons.

4.7.4 Mist Eliminator Design Factors

The design of a complete mist elimination system is complex, in that several conflicting objectives must be considered. The desire for high collection efficiency and methods to reduce reentrainment must be weighed against washability or susceptibility to plugging and high pressure drops. Design considerations must also include such factors as scrubber system design and operating conditions, construction, scrubbing media, solids content of the slurry, and sulfur content of the coal. Included in the design are the following four broad areas, all of which require specifications:

- Mist eliminator construction
- Mist eliminator equipment design
- Mist eliminator wash system
- General design factors

Each area is discussed in Sections 4.7.4 through 4.7.7. Discussion is confined to continuous or discontinuous baffle-type mist eliminators, since these types are preferred for lime scrubbing applications. The following important factors in mist eliminator specifications are discussed first:

- Mist eliminator shape
- Number of passes
- Spacing between vanes
- Slanted mist eliminator
- Materials of construction
- Special drainage devices

4.7.4.1 Mist Eliminator Shape--

The shape of the mist eliminator is determined by three factors: (1) whether vane design is continuous or discontinuous, (2) whether the continuous-vane type has sharp or rounded bends, and (3) the angle between the vanes. The continuous chevron-shaped mist eliminator is employed to a far greater extent than the baffle type in lime scrubbing applications. Its main advantages are greater strength and lower cost. Pressure drop is not a main consideration, neither for continuous nor for discontinuous chevron eliminators since the designs are similar.

Both sharp and smooth vane bends are employed in scrubbing operations but sharp-angled collectors predominate. Figure 4.7-8 illustrates the difference between the S- and the Z-shaped bends in the three-pass, continuous chevron mist eliminator. Sharp-angle bends provide greater collection efficiency, but they also have a greater tendency for reentrainment and plugging. Figure 4.7-8 also shows a 120-deg bend and a 90-deg bend chevron mist eliminator. The lower angle design causes more sudden gas direction changes and resultant greater primary collection efficiency.

4.7.4.2 Number of Passes--

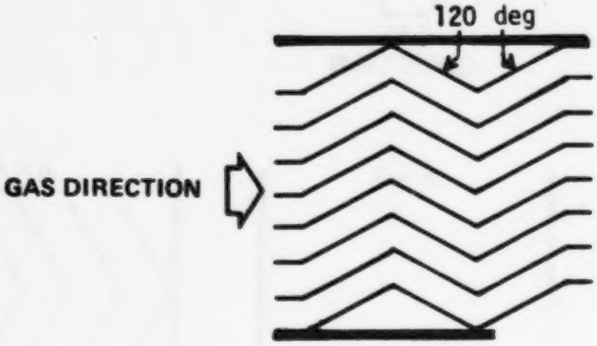
The number of passes in the mist eliminator corresponds to the number of direction changes the gas stream must make before it exits. Normally, the greater the number of passes there are, the greater the collection efficiency. Because of the high-solids environment of a lime scrubber, however, the more passes there are, the more likely it is that plugging will occur. Figure 4.7-9 shows a two-pass (V-shaped), a three-pass (Z- or S-shaped), and a multiple-pass chevron mist eliminator. Three-pass collectors, most commonly used in the lime and limestone systems, provide good collection efficiency (>90 %) with adequate washability.

4.7.4.3 Spacing Between Vanes--

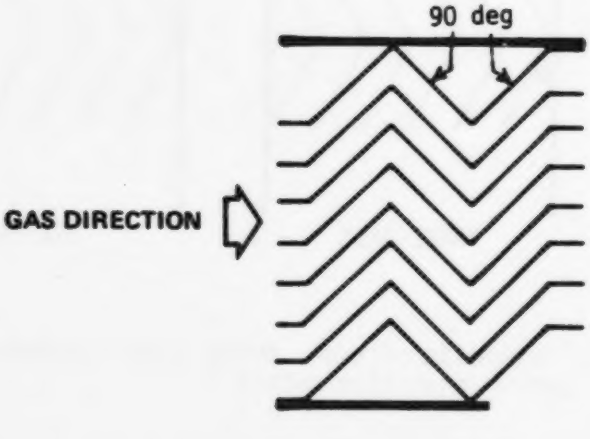
The spacing between individual chevron blades is an important factor in mist eliminator design. The closer the spacing is arranged, the better the collection but the greater the potential for plugging. Single-stage mist eliminator spacing ranges from 1.5 to 3 in.; if a second stage is used, the spacing is usually the same as that for the first stage. It can, however, be reduced to as low as 7/8 to 1 in. to provide higher collection efficiency.

4.7.4.4 Slanted Mist Eliminator[7]--

Figure 4.7-10 shows a Combustion Engineering design for a slanted mist eliminator (A-shaped, two stages, and two passes). It has better drainage than the conventional type, which helps reduce plugging and intermittent problems.


120 deg
GAS DIRECTION

CROSS SECTION OF THREE-PASS, 120-deg BEND CHEVRON
MIST ELIMINATOR


90 deg
GAS DIRECTION

CROSS SECTION OF THREE-PASS, 90-deg BEND CHEVRON
MIST ELIMINATOR

Figure 4.7-8. Mist eliminator designs showing the differences in baffle angle and the number of passes.[1]

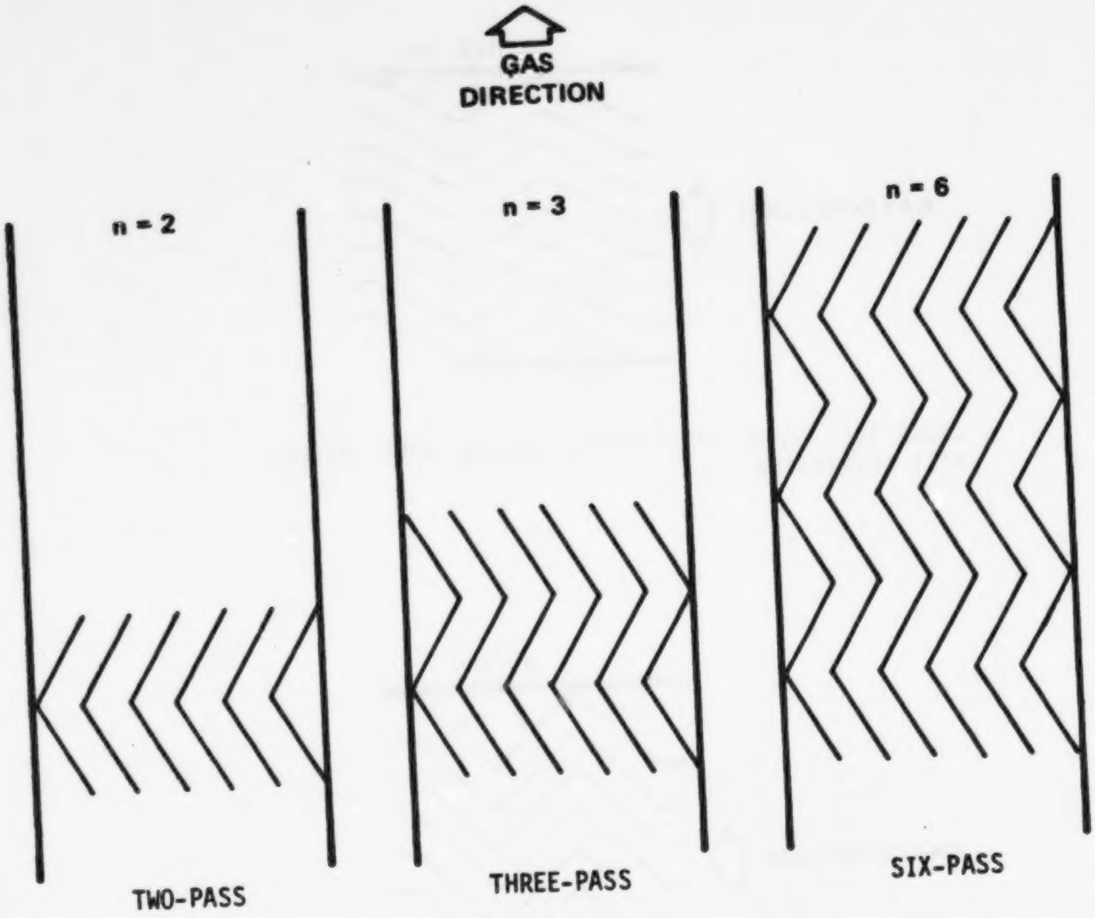

GAS DIRECTION
n = 2
n = 3
n = 6
TWO-PASS
THREE-PASS
SIX-PASS

Figure 4.7-9. Schematic of two-, three-, and six-pass chevron mist eliminators.[1]

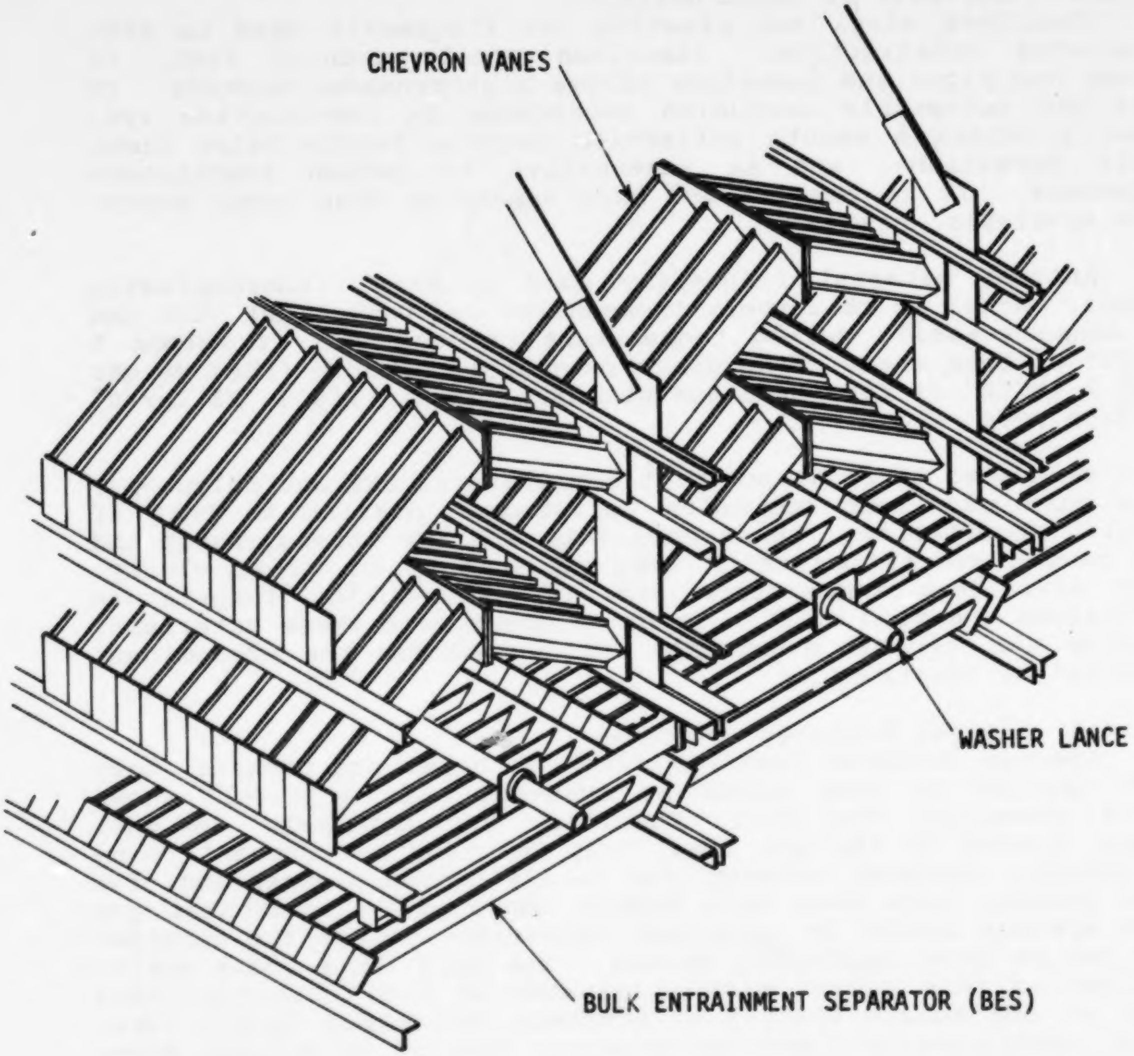

CHEVRON VANES
WASHER LANCE
BULK ENTRAINMENT SEPARATOR (BES)

Figure 4.7-10. Slanted mist eliminator for vertical gas flow.[7]

4.7.4.5 Materials of Construction--

Stainless steel and plastics are frequently used in mist eliminator construction. Stainless steel, usually 316L, is strong and rigid and therefore allows high-pressure washing. It also has acceptable corrosion resistance in low-chloride systems, provides a smooth collection surface (which helps limit scale formation), and is insensitive to sudden temperature increases. It is heavier and more expensive than other materials available, however.

Another material frequently used is Noryl (thermoplastic resin). Noryl is relatively inexpensive and very light, but can be damaged easily during temperature excursions. It weighs 5 lb/ft^2 of face area. Fiberglass reinforced plastic (FRP) weighs 5 to 7 lb/ft^2 of face area and stainless steel (316L), 22 lb/ft^2 of face area.

When used to construct mist eliminators, FRP and polypropylene have excellent corrosion resistance, similar to that of Noryl. Nevertheless, these materials are not strong enough and can become embrittled after long exposure to scrubbing slurry. They also have temperature limitations. During temperature excursions the risk of fire is quite great with these materials. Despite the various drawbacks, FRP has become the predominant material of construction.

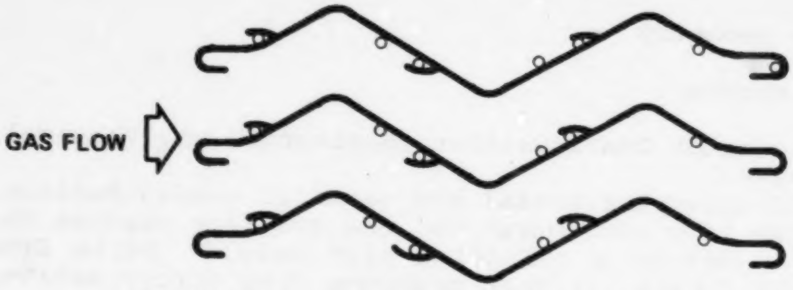
4.7.4.6 Special Drainage Devices--

Special drainage features, such as hooks and pockets, have been applied to lime scrubbing systems. Figure 4.7-11 shows three examples: the Heil, Peerless, and Matsuzaka designs. Hooks, placed in the gas flow, trap drainage and prevent reentrainment. Pockets, however, can easily become plugged and, for this reason, have been more widely employed in horizontal gas flow systems and/or in open-loop operations, where the eliminator can be more thoroughly washed. The only large-scale applications of this pocket mist eliminator by U.S. utilities have been at the Mohave Station of Southern California Edison (vertical configuration) and the Colstrip Station of Montana Power (horizontal configuration).

4.7.5 Mist Eliminator Equipment Design Considerations

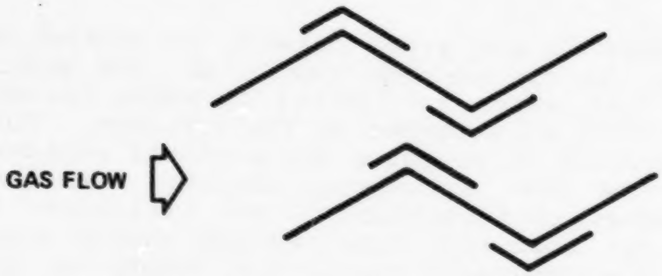
The following important topics in mist eliminator equipment design are discussed in this section:

- Mist eliminator configuration (horizontal vs. vertical gas flow)
- Use of bulk separation and knock-out devices
- Freeboard distance
- Number of stages



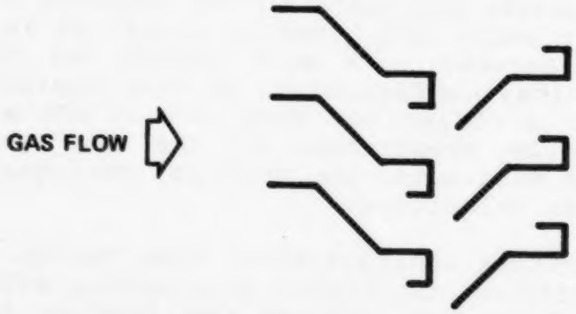
HEIL CHEVRON MIST ELIMINATOR WITH COLLECTION HOOKS

PLAN VIEW



PEERLESS CHEVRON MIST ELIMINATOR WITH COLLECTION POCKETS

PLAN VIEW



MATSUZAKA MIST ELIMINATOR WITH COLLECTION POCKETS

PLAN VIEW

Figure 4.7-11. Cross section of mist eliminator with special reentrainment-prevention features.

- Distance between stages
- Passage geometry
- Miscellaneous

4.7.5.1 Mist Eliminator Configuration (Horizontal vs. Vertical Gas Flow)--

Figure 4.7-12 shows horizontal and vertical configurations. In the vertical gas flow configuration, the gas flow opposes the path of drainage. Before a collected mist droplet falls from the mist eliminator blade, it must overcome drag forces exerted by the gas stream. The balancing of drag and gravitational forces results in a longer residence time of droplets on the blade, which increases the chance of scaling, plugging, and reentrainment. This is one of the disadvantages of the vertical gas flow configuration.

A second disadvantage is the water balance constraint on mist eliminator washing. In closed-loop operations, the available quantity of fresh wash water is limited by water balance requirements, since the water is returned to the scrubber. This limitation has often resulted in plugging and eventual shutdown of the scrubber system for mist eliminator cleaning. Another problem with the horizontal configuration is the limitation in wash water direction. The most effective washing should occur if water is admitted longitudinally along the length of the vane. The horizontal configuration admits wash water from the top face and/or bottom face of the mist eliminator only.

The use of mist eliminators in a vertical configuration with horizontal gas flow is nearly universal in the Japanese FGD industry; the mist eliminator units are normally installed in a separate chamber after the scrubber. A main reason for the efficient removal in the vertical configuration is that captured liquid flows continuously to a collection area and is not allowed to "pile up" only to be reentrained in the flue gas. Because reentrainment is more difficult, the vertical configuration can be operated at higher velocities.

The Japanese use the vertical configuration, even though it has greater capital cost, because the higher elimination efficiency effected by this configuration reduces the load on the reheater. As discussed earlier, another reason for the higher mist elimination efficiency achieved by the Japanese is their wide use of hooks and pockets.

In North America, researchers at TVA, Riley Stoker, and Ontario Hydro have recommended vertical mist eliminator systems. Weir horizontal scrubbers readily employ them since the scrubbed gas exits from the scrubber in a horizontal flow.

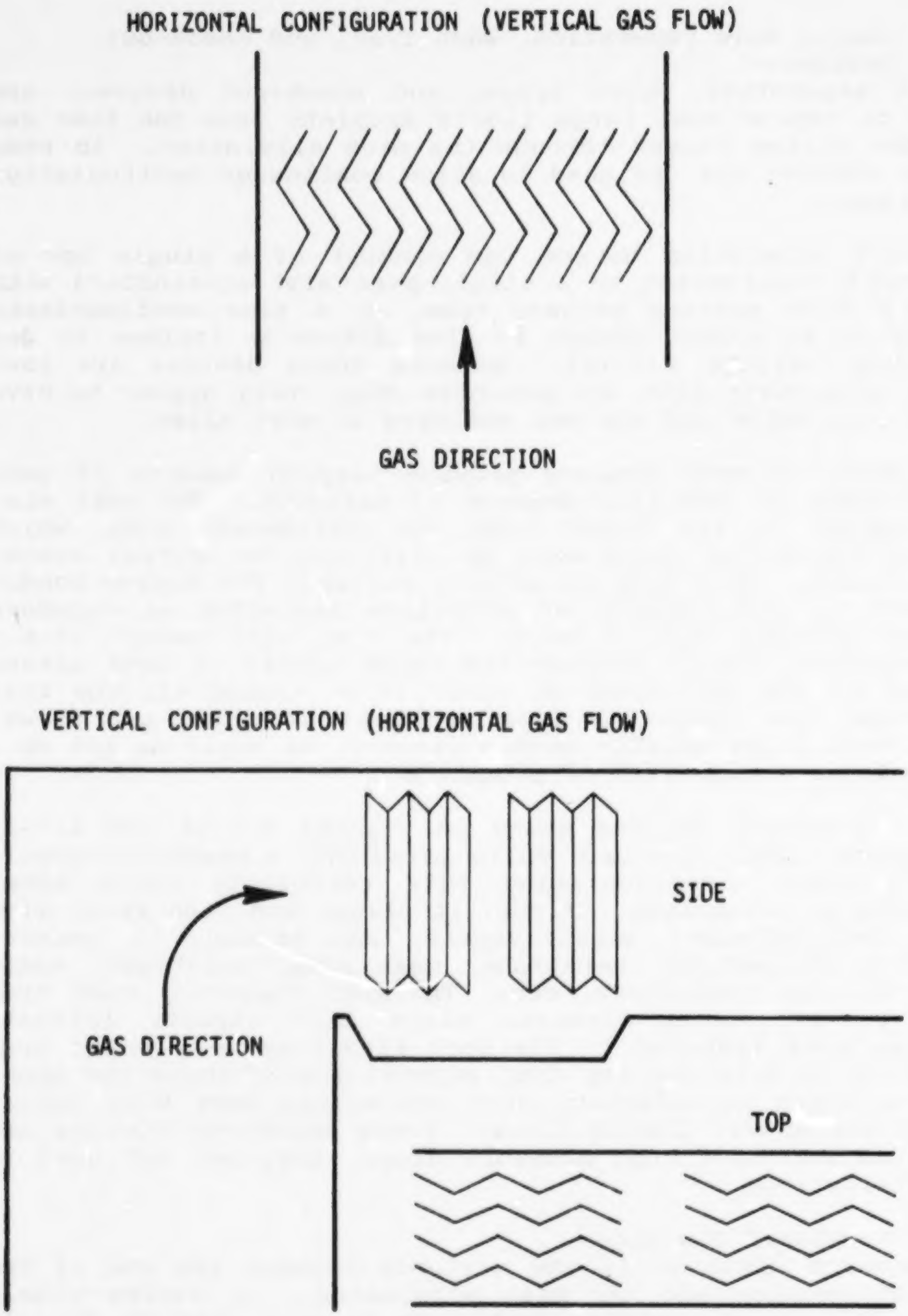

HORIZONTAL CONFIGURATION (VERTICAL GAS FLOW)
GAS DIRECTION
VERTICAL CONFIGURATION (HORIZONTAL GAS FLOW)
SIDE
GAS DIRECTION
TOP

Figure 4.7-12. Horizontal and vertical mist eliminators.

4.7.5.2 Use of Bulk Separation, Wash Tray, and Knock-out Devices--

Bulk separators, wash trays, and knock-out devices, are designed to remove most large liquid droplets from the flue gas before the stream passes through the mist eliminator. In some cases the devices are designed to allow continuous recirculation of wash water.

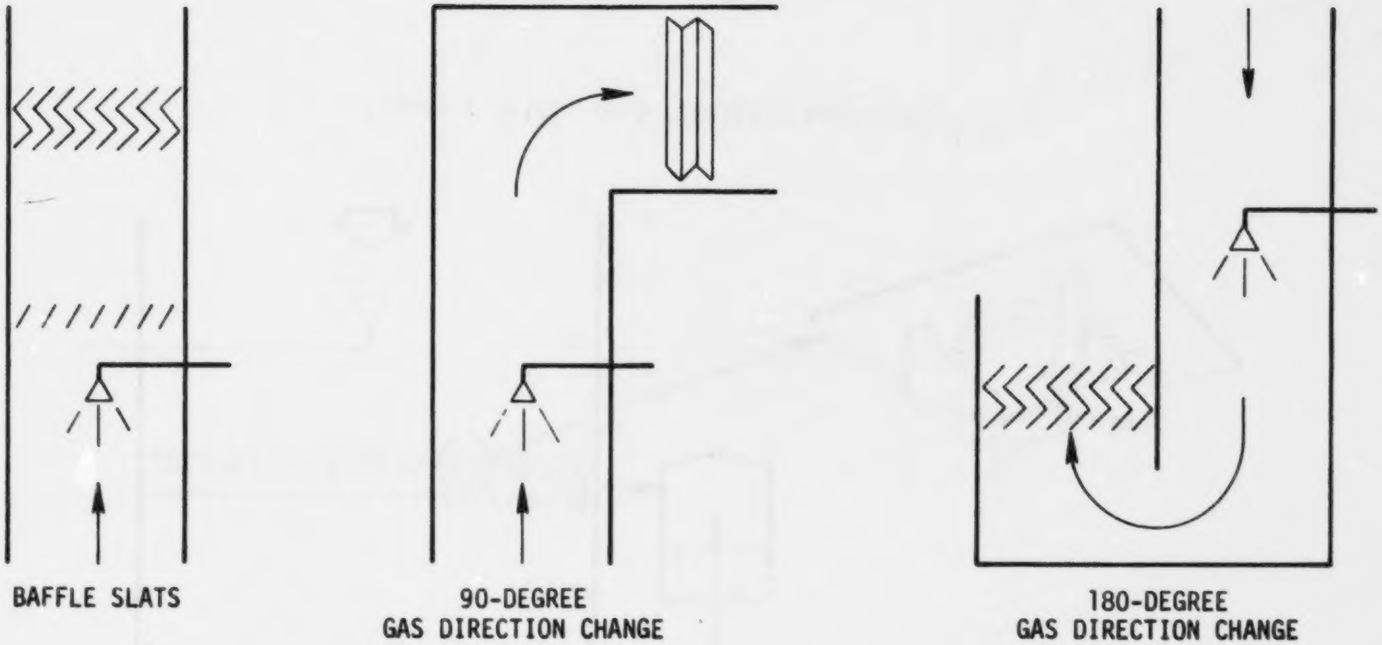
A bulk separation device can consist of a single row of baffle vanes (equivalent to a single-pass mist eliminator) with relatively wide spacing between them, or a flow configuration resulting in an abrupt change in flow direction (either 90 deg or 180 deg) (Figure 4.7-13). Because these devices are low-plugging separators with low pressure drop, they appear to have only marginal value and are not employed at most sites.

A number of tray designs provide varying amounts of gas-liquid contact at specific degrees of turndown. The most elementary design is the "wash" tray, or impingement tray, which employs a horizontal sieve deck to allow gas to contact cross-flowing liquid. This tray is usually suitable for design conditions, but is not capable of effective operation at turndown conditions greater than 4 to 1. The tray will "weep" (i.e., bleed excessive liquid through the holes before it gets across the tray) at low gas flows or "jet" (blow liquid off the tray and prevent the downcomer from sealing) at high gas flows. Holes in wash trays usually have a diameter as small as 1/4 in., which produces a high risk of plugging.

The knock-out devices shown in Figures 4.7-14 and 4.7-15 remove large liquid droplets while providing a means to recycle the wash water. Recirculating this relatively clean water offers several advantages. First, it allows the wash water flow rate to be increased significantly, and second, it permits flexibility in washing operations, wash water treatment, addition of scaling inhibitors, etc. The Koch Flexitray wash tray (Figure 4.7-14) is a discrete stage that effects intimate liquid-gas mass transfer.[8] The Koch Flexitray is a valve tray that employs a floating cap that adjusts itself above the opening to maintain satisfactory tray hydraulics over wide variations in gas and/or liquid flows. Since knock-out devices are complicated and have high pressure drops, they are not used at most installations.

4.7.5.3 Freeboard Distance--

Freeboard distance is the distance between the end of the absorption section and the mist eliminator. It varies widely among installations, ranging from 4 ft to more than 20 ft. In the freeboard area, entrained particles can coalesce and return to the scrubber solution by gravity before encountering the mist



BAFFLE SLATS

90-DEGREE
GAS DIRECTION CHANGE

180-DEGREE
GAS DIRECTION CHANGE

Figure 4.7-13. Bulk separation systems.[1]

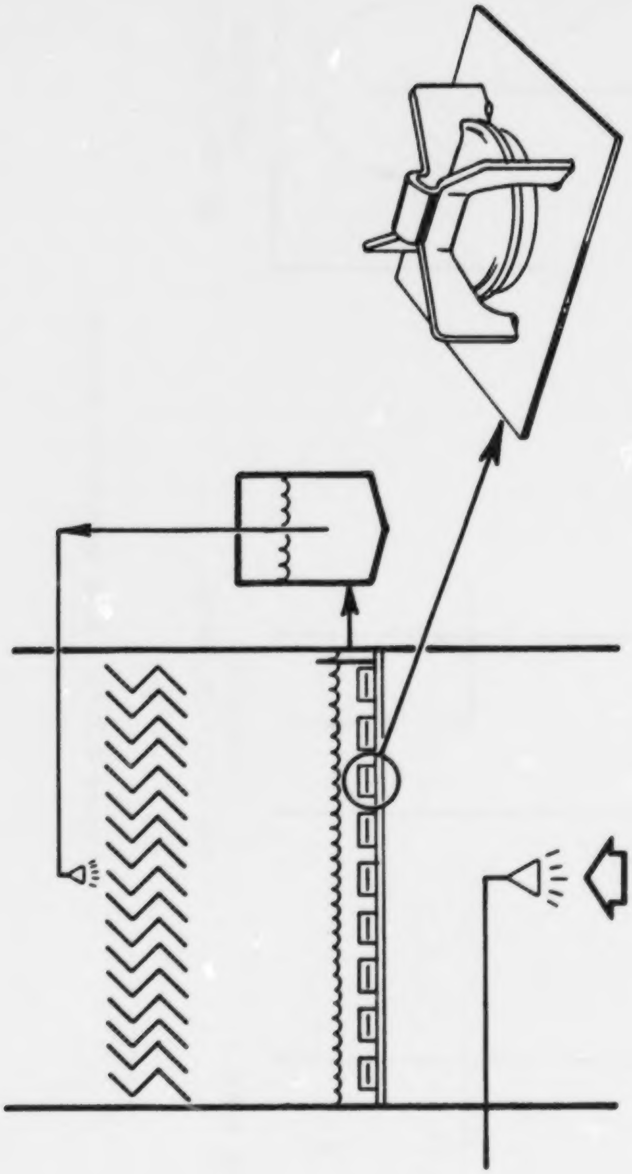


Figure 4.7-14. Koch Flexitray wash tray.[1]

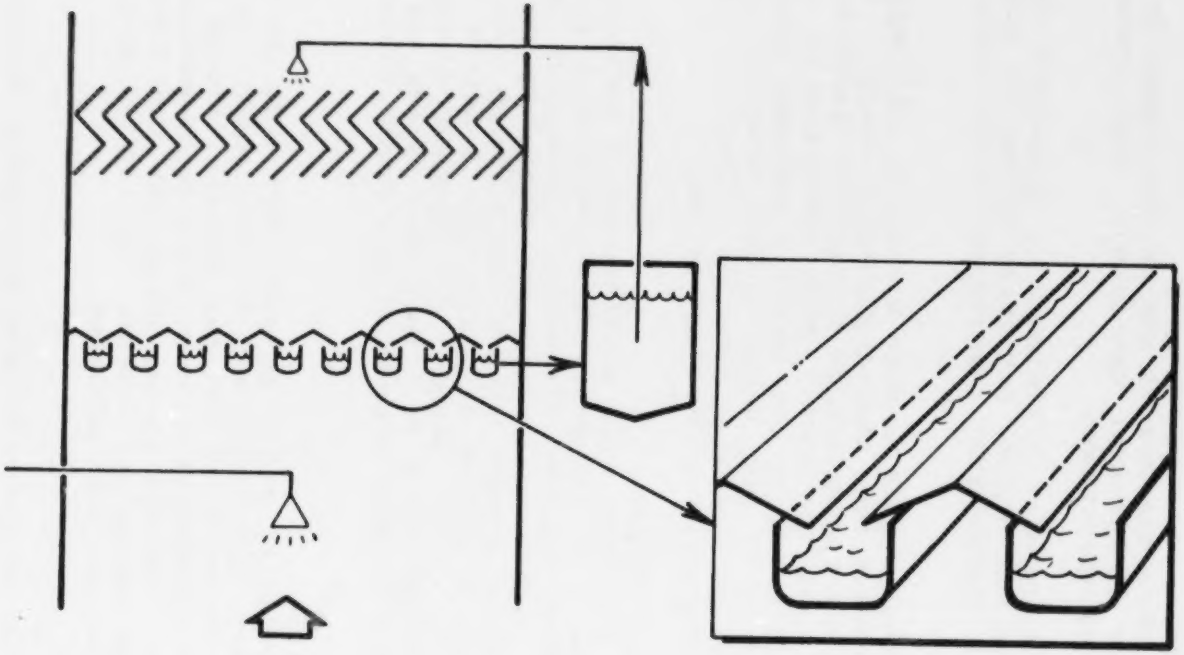


Figure 4.7-15. UOP trap-out tray.[1]

eliminator. Most particles that will settle are usually removed in the first 8 to 10 ft; the additional freeboard is not effective in removing the smaller entrained particles before they contact the mist eliminator.

4.7.5.4 Number of Stages--

Opinions vary regarding the use of one or two stages in a vertical mist eliminator (horizontal gas flow). Both systems are used in lime scrubbing operations.

Single-stage mist eliminator efficiency is increased with the use of a bulk separation device, but spray volume and pressure must be limited to reduce mist generation by the washing operation.

Although the two-stage system is more expensive and complicated, it has some advantages over the single-stage design. The first stage of a two-stage system can be rigorously washed from the front as well as from the back. Mist generated in the washing operation is collected in the normally unwashed second stage. A greater quantity of wash water, higher pressure, and greater duration of washing are also possible. There is also greater flexibility in designing a two-stage system.

4.7.5.5 Distance Between Stages--

Early designs of two-stage mist eliminators in horizontal ducts provided less than 1 ft between stages. With such short distances, severe plugging occurred frequently. Designers have subsequently achieved higher collection efficiency by high-volume washing of the first stages and including enough spacing between stages to allow entrained liquid drops to settle out before they contact the second stage. The optimum distance between stages is approximately 6 ft. This also allows sufficient space for personnel to walk between stages during cleaning periods.

4.7.5.6 Passage Geometry--

Superficial gas velocity plays an important role in the effectiveness of primary collection and reentrainment. In an attempt to adjust the velocity of the gas passing through the mist eliminator, some scrubbers have an enlarged cross-sectional housing in their design. Because of the uneven gas flow distribution caused by such an expansion, however, substantial gain in collection efficiency has not been achieved.

4.7.5.7 Miscellaneous--

Some thought should be given in mist eliminator design to features that will be useful during cleaning or replacement of the units. These could include a rectangular walkway, 2 by 6 ft, that would provide easy access and prevent maintenance personnel from having to stand on the eliminator, where their feet could be trapped between the blades. Standing on a corroded or embrittled mist eliminator could also cause it to collapse. Whatever the material of construction, mist eliminator sections should be light enough to be lifted easily by two people. Lightweight mist eliminators are easy to install and clean during maintenance periods.

Also of the utmost importance is the ability of the mist eliminator to operate satisfactorily under turndown conditions. Reduced gas flow through the eliminator will reduce the velocity of the gas, and the mist eliminator's efficiency will decrease to a very low level. Modular design of the eliminator is one way to solve this problem.[19]

4.7.6 Mist Eliminator Wash System

Design of the mist eliminator wash system has advanced greatly since the magnitude of the scaling and plugging problems first became evident. The following factors are important in the specification of a complete mist eliminator wash system:

1. Wash water type
2. Wash water direction (front, top, and/or back)
3. Wash direction and quantity of water (intermittent vs. continuous)
4. Wash water pressure
5. Type of coverage (total vs. partial)

4.7.6.1 Wash Water Type[2,7]--

Since the main purpose of mist eliminator washing is to clean off accumulated scale and mud deposits, fresh water is naturally preferred. For closed-loop lime scrubbing, 100 percent fresh-water washing is usually impossible. The normal procedure in lime scrubbing systems is to introduce all makeup fresh water (in excess of that required for pump seals and lime slaking) through the mist eliminator wash system. Additional wash water, which is sometimes required, is usually obtained by recycling clear water from the thickener or from the sludge pond overflow. The disadvantage of using this liquor is that it is already saturated with calcium sulfate. If lime carried up into the mist eliminator reacts with residual sulfur dioxide in the gas to form more calcium sulfate, then precipitation and scaling can occur. This sulfate-saturated recycle liquor, however, can be diluted with fresh water and chemically treated with soda ash to remove the calcium ion. In some cases, scrubber slurry can be used on the mist eliminator front-wash system, while fresh water or diluted recycle liquor from the thickener or sludge pond overflow can be used on the back-wash system.

4.7.6.2 Wash Direction--

The direction of wash water flow depends on the mist eliminator configuration and on the number of stages. With a horizontal configuration, washing is possible only from the bottom and top of the column. Using a vertical configuration, wash water can be directed horizontally from the front and/or back and vertically from the top. In all cases it has been found that washing in a direction countercurrent to the gas flow, or from the top in a vertical mist eliminator, generates large quantities of mist. A second-stage mist eliminator is therefore desirable when long-duration washing in those directions is planned. When a single-stage mist eliminator is actually specified, countercurrent washing is normally limited to short duration at high pressure and high volume, i.e., deluge or flush washing.

4.7.6.3 Wash Duration and Water Quantity--

Difficulty with scaling and plugging in the mist eliminator section of the scrubbing system has been primarily associated with the circulating wash system. At present, suppliers and operators are designing systems for washing from different directions using different wash durations and wash water pressures.

In lime scrubbing facilities, where slurries are normally composed of 5 to 15 percent solids and reagent utilizations are greater than 85 percent, plugging problems are less severe than in those systems that use limestone. An intermittent, short-duration spray is usually sufficient to keep the mist eliminator of a lime scrubbing facility relatively clean and operational.

An alternative scheme is to place the mist eliminator wash system in a separate, closed-loop mode. This is possible on vertical gas flow mist eliminators when devices such as the Koch Flexitray or UOP trap-out tray (Figures 4.7-14 and 4.7-15) are employed to collect the wash water for recycle. Horizontal gas flow mist eliminators can easily be placed in a closed-loop mode. Use of these devices can significantly increase the total quantity of wash water available, allowing when necessary the use of continuous, high-volume sprays for two-stage systems. However, a purge to the scrubber must be made to prevent supersaturation of the wash liquor.

4.7.6.4 Wash Water Pressure[2,7]--

Wash water pressures, which are important in the overall wash system, vary widely; both lime and limestone scrubbing systems use an intermittent flush spray at pressures ranging from 20 to 40 psig. Where fresh-water input is restricted, a moderately high-pressure, short-duration wash spray will usually maintain relatively clean collectors while conserving fresh water.

Incorporation of high-pressure washing procedures must be included in the original design. If not, certain design modifications must be made, such as replacing plastic blades with stainless steel blades or blades constructed of thicker, reinforced material, so they can withstand the additional stress of high-pressure washing.

4.7.7 General Factors

Several other factors remain outside the above specification categories:

- Mist eliminator operating pressure drop (for determination of pluggage)
- Overall collection efficiency
- Mist loading and particle size distribution

4.7.7.1 Mist Eliminator Pressure Drop--

Lime scrubbing installations experience less than 1 in. H_2O pressure drop in their mist eliminators when they are clean. As scale and mud deposits accumulate, however, pressure drop and reentrainment increase. A TVA publication reports one experiment in which a ΔP rise from 0.1 to 1 in. H_2O corresponded to a 50 percent blockage of the free area between the mist eliminator blades. In another experiment, the ΔP across the mist eliminator rose to over 5 in. H_2O during the course of one long run. Inspection showed that the mist eliminator was almost completely plugged by a soft, mudlike accumulation of entrained solids.[10] This pressure drop can be used as a control mechanism to determine the degree of pluggage present in an operating mist eliminator.

4.7.7.2 Overall Collection Efficiency--

Overall collection efficiency of a mist eliminator depends on several factors, including particle size, distribution of the mist, pressure drop, gas velocity, type and design of the eliminator, and the quantity of mud and scale on its surfaces. Overall collection efficiency is easily obtainable from measurements of similar equipment in liquid-only applications.[1] Data on actual lime or limestone scrubbing applications are either not easily obtained or they are not currently available. Because of the added complexity solids give to sampling and data interpretation, FGD system operators have not been able to measure inlet and outlet particle size distribution and solid and liquid particulate loadings. Consequently, evaluation and improvement of mist eliminator design have been based on other, less-precise criteria, e.g., in-line reheater tube plugging, stack corrosion, scaling, and/or corrosion of induced-draft fans. This area deserves additional study. Quick and accurate methods are needed to measure mist loadings and particle-size distribution.

4.7.7.3 Mist Loading and Particle-size Distribution--

Mist loading and particle-size distribution should be measured accurately to determine the removal efficiency of a mist eliminator. Determination of mist eliminator removal efficiency is important to evaluate the effectiveness of design modifications and parameters. The effect of gas velocity, L/G ratio, percent solids of the slurry, and other operational variables cannot be adequately evaluated unless mist loading and particle-size distribution are known. Until recently no simple, accurate method of measuring mist loadings and particle sizes had been available for lime scrubbing applications. Now it appears that CFH Research Laboratories has developed such a procedure, based on microphotographic methods.[11] Direct photographs of drops in their natural environment are made using a proprietary optical system. Figure 4.7-16 shows such a droplet-sizing photograph. The photographs are electronically scanned and the information fed directly to a minicomputer, which provides a statistical analysis (with accuracies of 10%) of the particle loadings, density, size distribution, and/or velocities. Both laboratory testing and direct field studies of nozzles, spray towers, cooling towers, mist eliminators, etc., may be possible with this system.[11] Figure 4.7-17 is a graph drawn from data collected by this method.

4.7.8 Existing Facilities (Experience and Equipment Detail)

This section summarizes operational and design experience with mist eliminators in lime systems and provides background information on the scrubbing facilities. Data from operational plants show that most lime scrubbing FGD systems can apparently operate the mist eliminators successfully with only intermittent mist eliminator washing and manual washing during shutdown periods. Both relatively high- and low-sulfur coals and different types of scrubbers are used in the systems without significantly affecting mist eliminator operation. Design factors for mist eliminators on lime scrubbing systems are summarized in Table 4.7-1.

Most mist eliminators used in lime systems are three- or four-pass, 90-deg bend chevron mist eliminators with vanes made of reinforced plastic and spaced 1 to 3 in. apart. The single-stage mist eliminators are housed in a nonexpanded vertical duct (top of scrubber) and placed 4 to 20 ft above the last absorbing

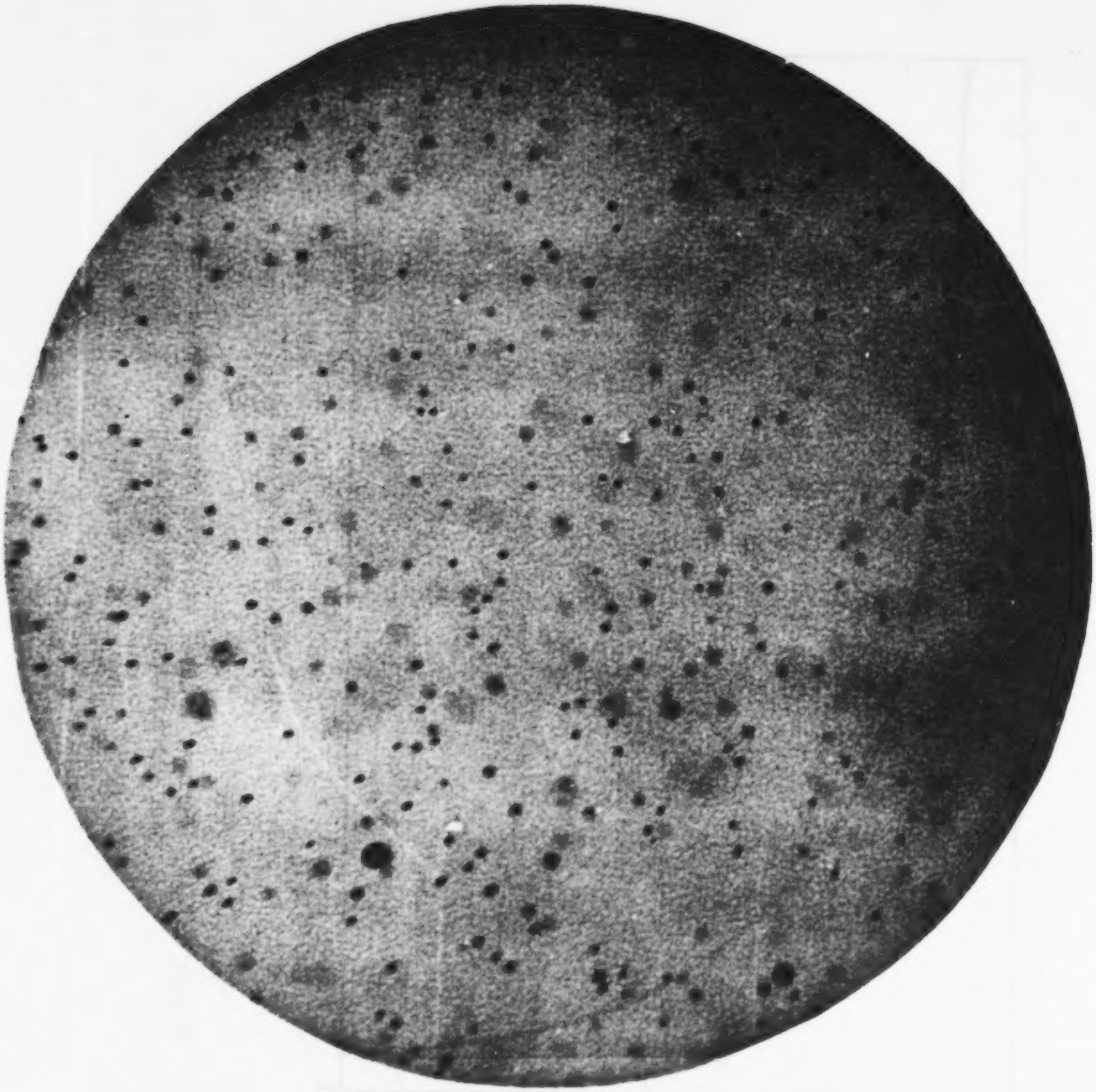


Figure 4.7-16. Droplet sizing photograph.

Courtesy CFH Research Laboratories.

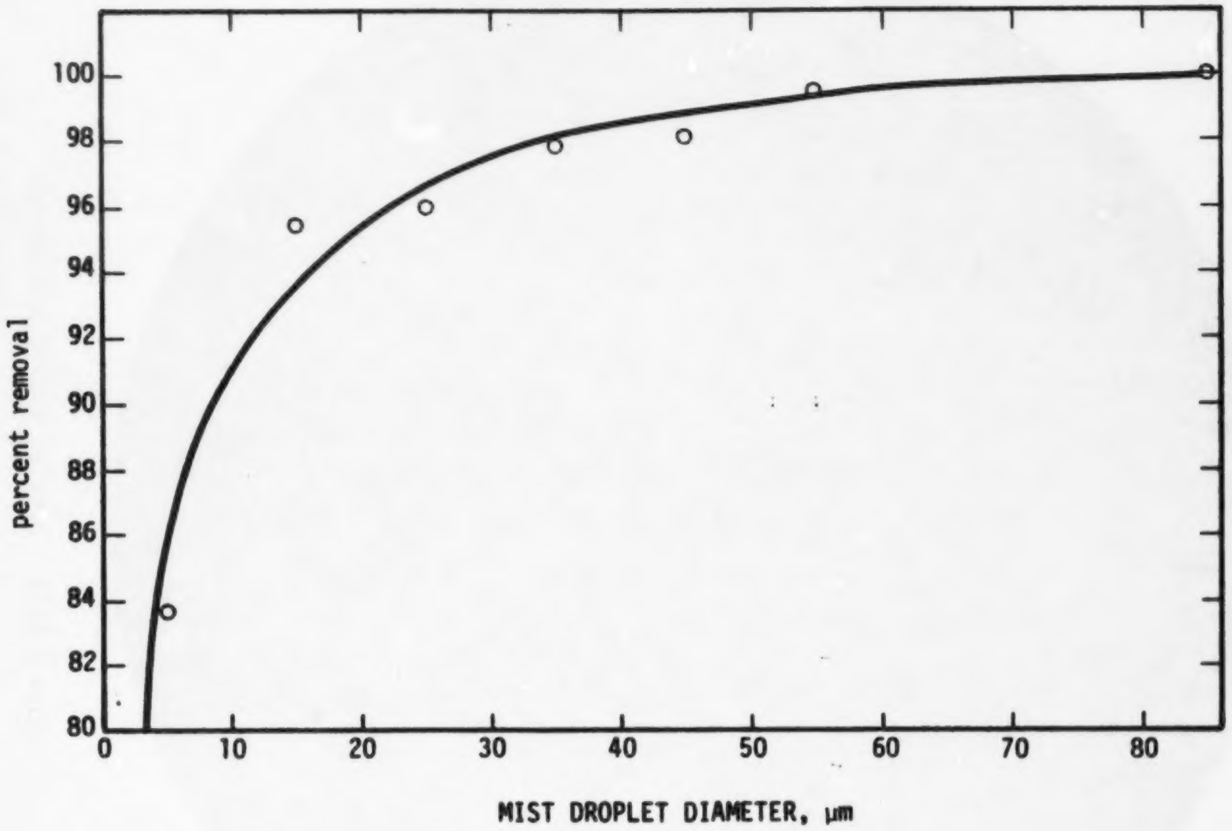


Figure 4.7-17. Percent removal vs. mist droplet diameter obtained by the application of the CFH method.[11]

Table 4.7-1. DESIGN FACTORS FOR MIST ELIMINATORS FOR LIME SCRUBBING SYSTEMS.[1]

Plant number	Plant name	Superficial gas velocity, ft/s	ME type	ME shape	Number of passes	Spacing between vanes, in.	Number of stages	Distance between stages, ft
1	Phillips	9-11	Chevron (Non-continuous)	Z-shaped 90° sharp-angle bend	3	3	1	NA
2	Paddy's Run	10	Chevron	Z-shaped 120°	3	1.5 to 2	2	NA
3	Elrama							
4	Green River 1 and 2	25-30	AAF radial vane	Curved vane	1	2.5-3.0 at inlet, 4.0 at outlet	1	NA
5	Bruce Mansfield 1	10	Chevron	Z-shaped	4	1-1.25	1	
	Bruce Mansfield 2							
6	Conesville 5	13.7 (calculated)	Chevron	Z-shaped 90° sharp-angle bends	3	2	2	4.5
7	Cane Run	10	Chevron	Rounded	3	1-1.5	2	6
8	Hawthorn	10	Chevron	Z-shaped	2	3	2	1.25
9	Colstrip 1 and 2	7.5	Heil Chevron	Smooth 120° with hooks	4	1	1	NA
10	Shawnee	9.4	Chevron	Z-shaped 90° sharp-angle bends	3	3.5-4	1	NA

(continued)

Table 4.7-1 (continued)

Plant number	Plant name	Type of knock-out tray	Material of construction	Total ΔP, in. H_2O	Collector combination	Distance between last absorption stage and ME
1	Phillips	None	FRP	4	Horizontal	4-5 ft
2	Paddy's Run	None	FRP	1	Horizontal slanted inverted V-shape	5 ft
3	Elrama	None	FRP	4	Horizontal	4-5 ft
4	Green River	None	Turning vanes stainless steel, outside collection area coated mild steel	2.3	Horizontal	10-15 ft
5	Bruce Mansfield 1	None	NA	0.5-0.75	Horizontal	NA
	Bruce Mansfield 2					
6	Conesville 5	UOP trap-out tray	Stainless steel	1.6 - 1st stage 0.3 - 2nd stage	Horizontal	10 ft total. 6 ft from absorber nozzle to tray. 4 to 5 ft from tray to ME
7	Cane Run 4	None	Stainless steel	0.5 - 1.2		
8	Hawthorn	None	FRP	1.2	Horizontal slanted inverted V-shape	10 ft
9	Colstrip 1 and 2	-	PVC	0.3	Horizontal	13 ft. 5 ft between spray nozzle and wash tray. 8 ft between wash tray and ME
10	Shawnee	-	316 SS	0.5	Horizontal	4 ft

(continued)

Table 4.7-1 (continued)

Plant number	Plant name	Wash water type	Wash duration	Wash water pressure, psig	Wash rate (per module), gal/min
1	Phillips	River water	5 min every 2 h	Underwash: 15-20 Topwash: 40	Topwash: 60-70 Underwash: 125
2	Paddy's Run	River water	10-15 min every 8 h	40-65	80-200
3	Elrama				
4	Green River 1 and 2	River water treated	Continuous	50	45
5	Bruce Mansfield 1	Recycle water from thickener overflow	Intermittent	30	60
	Bruce Mansfield 2				
6	Conesville 5	River water	Continuous both stages	86	1st stage: 500 2nd stage: 500 Tray wash: 90
7	Cane Run 4	River water	2 min every 5 min	70	40
8	Hawthorn	River plus thickener	1 to 1.5 h every 3 days (apx.)	100 to 120 manual wash; 70 with wash lance	2000
9	Colstrip 1 and 2	Underwash: pond overflow and river water. Topwash: river water. Wash tray: fresh water in closed-loop system.	Underwash: continuous Topwash: 24 min every 24 h	40-50	Topwash: 390 Underwash: 30
10	Shawnee	River water	Intermittent	Topwash: high pressure. Underwash: low pressure.	Topwash: 100 every 80 min Underwash: 750 every 4 h

NA - Not available.

stage in the nontilted horizontal configuration. Superficial gas velocities ranged from 7.5 to 21.6 ft/s with most ranging from 9 to 14 ft/s.

4.7.8.1 Phillips Station (Duquesne Light Company)[12]--

The mist eliminator at Phillips Station, supplied by Chemico, started operation in 1973. The system has an internal mist eliminator within the venturi before the wet scrubber induced-draft fans. The system also has a large knock-out chamber and mist eliminator after the fan. The internal mist eliminator plugged frequently before the system was changed to a continuous wash under the mist eliminator. Although this reduced the pluggage or scaling problem, it is doubtful that the mist eliminator is effective. Better washing reduces buildup on the induced-draft fan. Therefore, a good internal mist eliminator is not required. Effective mist elimination probably occurs in the large external mist eliminator, since few problems have been reported and the mist eliminators are only washed daily.

4.7.8.2 Paddy's Run 6 (Louisville Gas and Electric Company)[13]--

The mist eliminator at Paddy's Run 6 was supplied on a marble-bed absorber by Combustion Engineering. It has been in operation for the last 4-1/2 years and has remained clean and pluggage-free. Its trouble-free operation may be attributed to the use of carbide lime. When a change was made from carbide lime to high-calcium commercial grade lime, scaling and plugging occurred.

4.7.8.3 Elrama Station (Duquesne Light Company)[14]--

The mist eliminator on a venturi scrubber at Elrama Station was supplied by Chemico and has been in operation since August 1975. It, too, was redesigned by Gibbs & Hills, Inc., in 1975. Less scaling and plugging have been reported since redesign, though it is doubtful whether the mist eliminator is effective. This system, like that of Phillips, has large external mist eliminators in knock-out chambers.

4.7.8.4 Green River Station (Kentucky Utilities)[15]--

The radial-vane mist eliminator, on a mobile-bed absorber, was supplied by American Air Filter (AAF). Severe scaling and plugging of the scrubbers system's downstream equipment were caused by slurry carryover and low efficiency of the mist eliminator. Some modifications are proposed to improve the eliminator's performance. However, at the time of writing, the modifications had not yet been carried out.

4.7.8.5 Bruce Mansfield (Pennsylvania Power Company)[16]--

The mist eliminators on venturi scrubbers at Bruce Mansfield Station were supplied by Chemico. All have been in operation since June 1976.

One of the mist eliminators on the scrubber became plugged very soon after the operation began, probably because gas flow through the scrubber was much higher than designed. The material plugging the mist eliminator hardened to a point where it could not be removed and the entire unit was replaced. These mist eliminators are normally cleaned by intermittent spraying with recycled water. To prevent the problem of plugging, a system was installed that permitted the mist eliminator to be flooded with large volumes of water in the event of excessive pressure drop across the device.

Despite this new wash water piping, as of this writing, the mist eliminators are still plugging with hard scale, and periodically they must be manually cleaned. Even at design flow, these units are not meeting the design criteria of 1 g/ft^3 carryover. Tests have indicated that mist carryover from the mist eliminator is from 2 to 3 g/ft^3.

In an attempt to solve this problem, a section of vertical mist eliminator (horizontal gas flow) was installed in the outlet within the second-stage venturi (absorber) vessel, adjacent to the outlet opening. It was intended to provide a large area, and therefore a velocity of about 20 ft/s. The strength of the structure was not sufficient to withstand the forces of excessive turbulence that occur in this area of the absorber resulting in the failure of this mist eliminator. It was then decided to install a smaller section of the vertical mist eliminator farther back in the outlet ductwork, where the velocity is about 50 ft/s. Within a few minutes of operation, the mist eliminator module collapsed and was scattered in small pieces throughout the ductwork. The manufacturer supplied a new, heavier module and the supervision to install it. This mist eliminator was put in service May 23, 1977. During June 1977, Chemico conducted model studies on both the horizontal and vertical mist eliminators. Full-sized mist eliminator sections were used in the module studies; information gained from the study provided the operating company with valuable design criteria. The study revealed that pressure drops in excess of 0.75 to 1 in. H_2O allowed excessive carryover from the horizontal mist eliminators. When pressure drop was maintained at 0.5 in. H_2O or less, there was practically no carryover of entrained water.

4.7.8.6 Conesville (Columbus and Southern Ohio Electric Company)[17]--

The mist eliminator on a turbulent contact absorber at Conesville Station was supplied by UOP. It has been in operation since July 1976. No operational problems are reported and the unit has remained clean and plug-free. Thiosorbic lime is used in this system.

4.7.8.7 Cane Run (Louisville Gas and Electric Company)[13]--

The radial vane mist eliminator on a mobile-bed scrubber at Cane Run was supplied by AAF. The scrubber system started-up in August 1976. Large pressure drop through the eliminator cut holes through it and caused mist carryover. In addition, slurry carryover caused scaling and plugging. The scrubber was shut down April 18, 1977, together with the boiler, for a projected 2-month overhaul, during which the mist eliminator was removed by cutting an 18-in. hole in its top section. This section was replaced with two banks of chevron baffles and an associated spray washing system. Since startup in July 1977, the chevron mist eliminators have operated quite well and have remained very clean.

4.7.8.8 Hawthorn (Kansas City Power & Light Company)[18]--

The mist eliminator on a marble-bed absorber at Hawthorn was supplied by Combustion Engineering. The scrubber system (limestone) started up in August, 1972. Since January 1977, this system has been operated in a lime scrubbing mode. After switching to low-sulfur coal burning, the utility has had no problem with the mist eliminator.

4.7.8.9 Colstrip (Montana Power Company)[19]--

The mist eliminators at Colstrip were supplied by Heil Process Equipment Company. The eliminator in Unit 1 was damaged by temperature excursions and had to be replaced. The new eliminator in Unit 1 has been in operation since October 1975, that in Unit 2 since May 1976. Washing with 78 percent tray pond return water and 22 percent river water has kept the mist eliminators scale- and plug-free.

4.7.9 Recommendations

In view of the above discussion, some recommendations for mist eliminator design and operation are summarized below:

1. The continuous chevron is better than the noncontinuous chevron because of its greater strength and relatively lower cost.

2. The closer the spacing, the better the mist collection efficiency and the greater the tendency for plugging. First-stage spacing may be from 1.5 to 3 in. The second-stage spacing can be as narrow as 7/8 to 1 in.

3. Special features such as hooks and pockets are desirable in vertical mist eliminators to decrease reentrainment in systems with proper scrubber chemistry to reduce plugging NO_x scaling.

4. When compared with the horizontal configuration, vertical configuration (horizontal gas flow) has the advantages of higher efficiency at high loadings and better washability; however, the capital cost is higher.

5. Freeboard distance should normally be 4 to 6 ft.

6. Bulk separation and knock-out devices are recommended. Proper lime utilization, scrubber gas velocity, and proper chemistry may reduce the need for bulk separation.

7. Intermittent high-pressure, high-velocity wash is better than continuous wash.

8. Noryl, FRP, and polypropylene as materials of construction are relatively lightweight and inexpensive compared with stainless steel. However, the protection provided by stainless steel during temperature excursions should be weighed against the cost. Stainless steel (316L) should not be used in high-chloride (greater than 2300 ppm) systems.

REFERENCES

1. Conkle, H. N., H. S. Rosenberg, and S. T. DiNovo. Guidelines for the Design of Mist Eliminators for Lime/Limestone Scrubbing System. EPRI FP-327 (Research Project 209), Battelle Columbus Laboratories, December 1976.

2. Heilex-EB, Mist Eliminator Blades. Bulletin B-922-1, Heil Process Equipment Company, Cleveland.

3. Private communication with R. Centa, J. Gavin, and J. Jackson, Heil Process Equipment Company, Cleveland.

4. Humboldt Lamellar Mist Separator. Bulletin, Matsuzaka Company (America), Inc., Oak Brook, Illinois.

5. Euroform Mist Eliminators. Bulletin ETS-1, The Munters Corporation, Ft. Myers, Florida.

6. Wet Scrubbing Systems for Air Pollution Control. Bulletin KPCZ, Koch Engineering Company, New York.

7. Green, K., and J. R. Martin. Conversion of the Lawrence No. 4 Flue Gas Desulfurization System. In: Symposium on FGD, Hollywood, Florida, November 8-11, 1977.

8. Private communication with R. Schwartz, Koch Engineering Company, New York.

9. Private communication with T. Moraski, EPRI, Palo Alto, California.

10. Schult, J. J., et al. Performance of Entrainment Separation in Slurry Scrubbing Process. Bulletin Y-93, National Fertilizer Development Center, Tennessee Valley Authority, Muscle Shoals, Alabama, June 1975.

11. Private communication with F. Hoffman, CFH Research Laboratories, Springfield, Massachusetts.

12. Private communication with J. Malone, Phillips Station, Duquesne Light Company, South Height, Pennsylvania.

13. Private communication with R. Van Ness, Paddy's Run Station, Louisville Gas and Electric Company, Louisville.

14. Private communication with F. Bork, Elrama Station, Duquesne Light Company, Elrama, Pennsylvania.

15. Private communication with J. Reisenger, Green River Station, Kentucky Utilities, Central City, Kentucky.

16. The Wet Scrubber Newsletter. The McIlvaine Company, No. 38, August 31, 1977, p. 7.

17. Private communication with D. Boston, Conesville Station, Columbus and Southern Ohio Electric Company.

18. PEDCo Environmental, Inc. FGD Summary Report. EPA 68-01-4147.

19. Grimm, C., et al. Particulate and SO_2 Removal at the Colstrip Station of the Montana Power Co. In: 2nd Pacific Chemical Engineering Congress, Denver, August 1977.

CONTENTS

4.8 FANS

Page

4.8.1 Introduction 4.8-1

4.8.2 Service Description 4.8-1

4.8.3 Design Parameters 4.8-2

  4.8.3.1 Location 4.8-2
  4.8.3.2 Temperature Increase 4.8-5
  4.8.3.3 Wet Fan 4.8-6

4.8.4 Materials of Construction 4.8-6

4.8.5 Existing Facilities 4.8-8

  4.8.5.1 Cane Run Power Station 4.8-8
  4.8.5.2 Green River Power Station 4.8-9
  4.8.5.3 Conesville Power Station 4.8-9
  4.8.5.4 Paddy's Run Power Station 4.8-10
  4.8.5.5 Phillips Power Station 4.8-10
  4.8.5.6 Bruce Mansfield Power Station 4.8-11

References 4.8-13

Bibliography 4.8-14

4.8 FANS

4.8.1 Introduction

Fans are used to drive gas through lime scrubbing FGD systems. These fans are radial-flow (or centrifugal) types, in which the gas flow is at right angles to the axis of motor rotation. Fan operation can be wet or dry. Dry fans operate at temperatures higher than the dew point of the species present in the flue gas. Wet fans operate in a flue gas atmosphere saturated with water.

In this report, the fans are called forced-draft (FD), induced-draft (ID), or ID booster fans, depending on the location and the role of the fan in the lime scrubbing system. The term "forced draft" is used when air or flue gases flowing in a scrubber system are maintained at pressures above atmospheric pressure (this fan is the induced-draft fan of the boiler system).

When air or flue gas flows in a unit under the influence of a progressively decreasing pressure below atmospheric pressure, the system is said to be operating under induced draft. This term is used to describe a booster fan installed downstream from the reheater.

Since the fan application in a scrubber system is very similar to that in a boiler system, power plant engineers are familiar with the performance and the mechanical design of these fans. Thus, only operational and process design features unique to a lime scrubbing FGD system will be presented in this section.

4.8.2 Service Description

Fans are installed in the system to handle gases coming from a boiler or a scrubber. The gas flow rates range from 300,000 to 500,000 acfm, and the temperature ranges either from 300° to 340°F or from 110° to 200°F, depending on the fan's location in the scrubbing system. The gas may contain moisture, particulates, sulfur dioxide, and/or acid mist. Particulates are generally abrasive and if wet tend to form scale or build up on the fan blades.

When a fan is upstream from a scrubber or downstream from a reheater, the gas temperature is higher than the water saturation temperature. Therefore, water will not condense on the fan and the operation is dry. When a fan is located between two scrubbers or between a scrubber and a reheater, entrained and condensed water cause the fan operation to be wet. This type of operation may require wash sprays on the fan to eliminate the solids buildup. In a high-sulfur coal application, the fan wash will have a tendency to absorb SO_2, turning the water acidic. Care must be taken, therefore, in the selection of materials of construction or lining for these wet fans.[1-5]

Because very few applications permit fans to operate continuously at the same pressure and volume, some convenient means of volume control through the fans is needed to maintain scrubber and boiler load requirements. This is commonly achieved with a variable-inlet vane or damper(s) as well as variable speed controls on the fans themselves.

The centrifugal action of a fan imparts static pressure to the gas. The diverging shape of the scrolls (curved portion of the fan housing) also converts a portion of the velocity head into static pressure. Although the normal static pressure requirement is approximately 20 in. H_2O, scrubber system designers commonly add 15 to 25 percent to the net static pressure requirement when purchasing a fan as a safety requirement to allow for buildup of deposits in ductwork and the inherent inaccuracies of the calculation.

4.8.3 Design Parameters

4.8.3.1 Location--

A scrubber FD fan in a lime FGD system (Figure 4.8-1) delivers hot gas to a scrubber. The gas temperature is higher than the acid dew point and there is no corrosion problem; however, unless a precipitator is located upstream (as shown in Figure 4.8-1), the gas contains abrasive fly ash, which may cause erosion in the fan. The gas flow rates are usually high because of the high temperature, which requires a larger capacity fan and a higher operating cost. A system with a scrubber FD fan operates under pressure as described in Section 4.8.1. Therefore, any leaks that develop are easily noticeable by corrosion products on the metal surface or discoloration of the metal surface.

A system with an ID fan (Figure 4.8-2), on the other hand, operates slightly below atmospheric pressure. If leaks develop in this system, air may be drawn in, causing undesirable oxidation of the scrubbing solution; such leaks will also increase the volume of air that must be handled. Unlike the leakages in the scrubber FD fan system, this type of leak is very difficult to detect. Generally the ID fan handles less gas volume than the FD fan because of the cooler gas temperature even though it is usually located after the reheater. Its operation is considered dry though gas from the reheater may contain acid mist

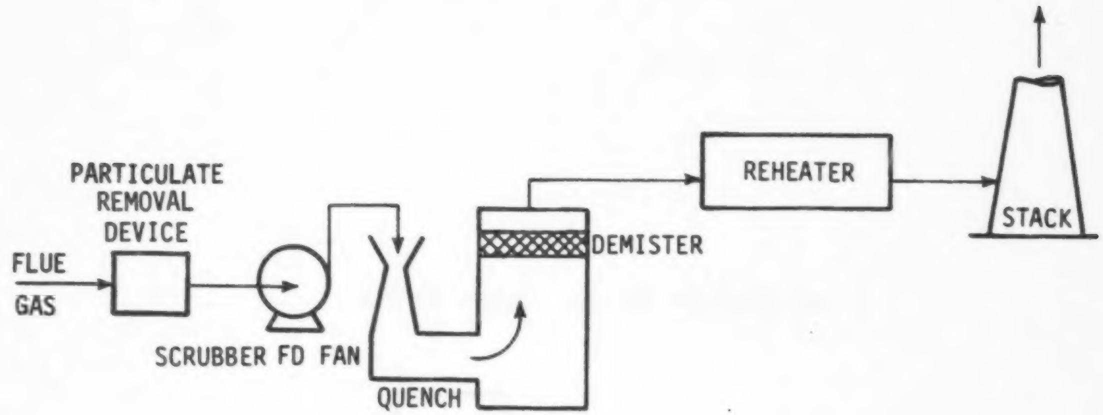

PARTICULATE
REMOVAL
DEVICE
FLUE
GAS
SCRUBBER FD FAN
QUENCH
DEMISTER
REHEATER
STACK

Figure 4.8-1. Scrubber FD fan application.

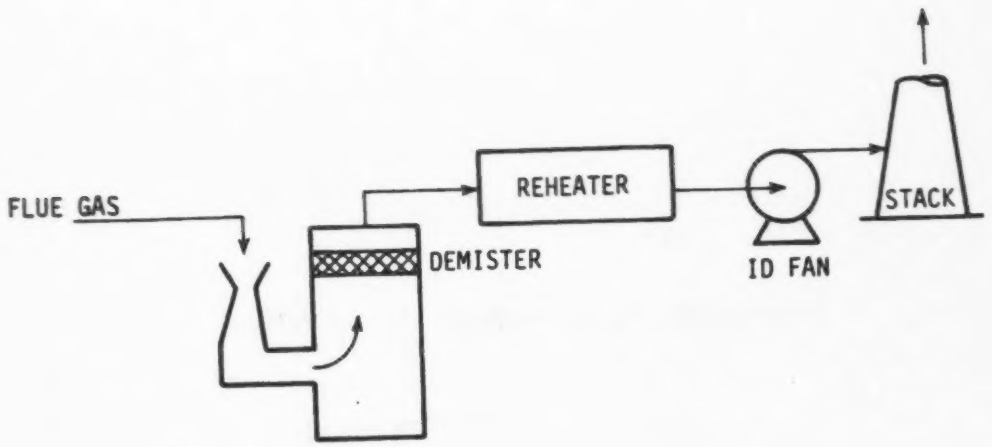

FLUE GAS
DEMISTER
REHEATER
ID FAN
STACK

Figure 4.8-2. ID fan application.

carry-overs and particulates, which could cause corrosion, erosion, and scaling problems in the fan. Such problems normally originate from poorly designed or operated mist eliminators.

4.8.3.2 Temperature Increase--

The adiabatic compression process of a centrifugal fan will increase the gas outlet temperature according to the equation:

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

or

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{R/C_p}$$

where Subscripts 1 and 2 denote the inlet and outlet conditions, respectively, and

T = temperature (T)

p = pressure (M/Lt^2)

$\gamma = C_p/C_v$ (dimensionless)

R = the gas constant (ML^2/t^2 T mole)

C_p = heat capacity at constant pressure per unit mass (L^2/t^2 T)

C_v = heat capacity of constant volume per unit mass (L^2/t^2 T)

The dimensions L = length, t = time, T = temperature, M = mass are given in brackets.

Suppose for a scrubber ID fan:

T_1 = 166°F
P_2 = 14.69 psia
ΔP = 20 in. H_2O = 0.72 psia
and C_p = 7.4186 Btu/lb-mol-°R
then $P_1 = P_2 - \Delta P$
= 14.69 - 0.72 psia
= 13.97 psia,

and $T_2 = (166 + 460°\text{R})\left(\frac{14.69\text{ psia}}{13.97\text{ psia}}\right)^{1.987/7.4186}$
= 634.5°R
= 174.5°F

Therefore, the theoretical temperature increase in the ID fan is:

$$\Delta T\ (\text{ideal}) = T_2 - T_1 = 174.5 - 166 = 8.5°\text{F}$$

For a scrubber FD fan:

$T_1 = 285°\text{F}$
$P_1 = 14.69$ psia
$\Delta P = 20$ in. H_2O
and $C_p = 7.4186$ Btu/lb-mol-°R
then $P_2 = P_1 + \Delta P$
$= 14.69$ psia $+ 0.72$ psia
$= 15.41$ psia

$$\text{and}\quad T_2 = (285 + 460°\text{F}) \left(\frac{15.41\ \text{psia}}{14.69\ \text{psia}}\right)^{1.987/7.4186} = 754.6°\text{R} = 294.6°\text{F}$$

Therefore, the theoretical temperature increase in a scrubber FD fan is:

$$\Delta T\ (\text{ideal}) = T_2 - T_1 = 294.6 - 285 = 9.6°\text{F}$$

The actual temperature increase in the fan operation is a little higher because the fan efficiency is less than 1 (~0.8-0.9).

The temperature increase due to the ID fan operation is an added advantage because it will lower the reheater duty.

4.8.3.3 Wet Fan--

A typical wet fan application is shown in Figure 4.8-3. The gas from the prescrubber is saturated with water and contains acid mists and abrasive carry-overs. Even though water sprays are installed to clean the fan internals, corrosion, erosion, and scaling can present continual problems. Buildup of solids on the fan blades causes severe corrosion and rotor imbalance, which in turn lead to higher noise levels, excessive vibration, and finally to fan failure. Because of these limitations, wet fans are usually not designed into the scrubbing system. However, if they are designed into the system, protection against corrosion is essential.

4.8.4 Materials of Construction

Fans in dry operation are often constructed of carbon steel and seldom experience serious problems since they are not subjected to the intense corrosive conditions normally found in a

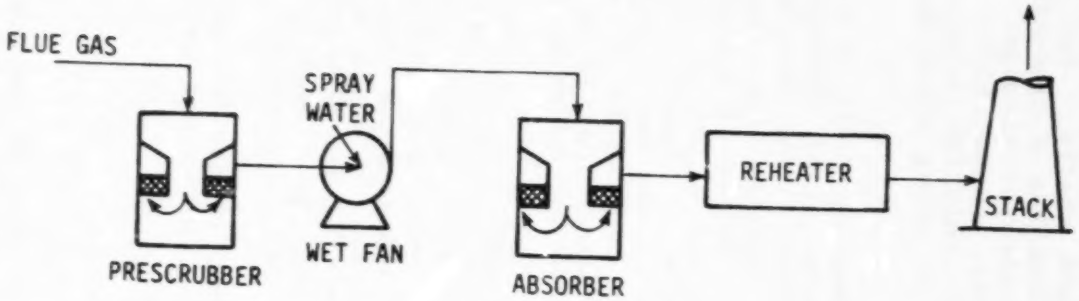

FLUE GAS
SPRAY WATER
WET FAN
PRESCRUBBER
ABSORBER
REHEATER
STACK

Figure 4.8-3. Wet fan application.

ID with respect to prescrubber.
FD with respect to absorber.

wet fan. Care must be taken, however, to minimize the abrasive effects of the particulates found in flue gases.

In wet-fan operations, high levels of acidity (pH of about 2.0) and chloride ions caused pitting attack and stress-corrosion cracks.[3,4,6] Thus, wet fans require special materials of construction. Alloy steels are the most common materials used to reduce corrosion of impellers and shafts. For example, a wet-type fan at Phillips Power Station has a Carpenter 20 Cb 3 impeller and 316L shaft, shaft shrouds and sleeves, inlet dampers, and stiffener bars.[3,4] However, it should be noted that stainless steels are susceptible to chloride stress-corrosion cracking and care should be taken in using these materials in such environments.

Protective coatings such as rubber or resin on standard fan housings and impellers of mild carbon steel construction have proved satisfactory in some applications. The increasing use of rubber (about 1/4-in. thick) for coating fan impellers and housings deserves special attention. Rubber is one of the least porous of materials and, when vulcanized to the metal, surrounds and protects it from corrosive gases or fumes. It also can withstand the high stresses set up in the fan and is flexible enough to resist cracking. However, bonding failures have been a problem when the coating has not been applied properly. As with any lining, temperature excursions can be determined.

Most fan damage or failure is caused by separation of the coating from the metal or by damage to the coating by solid debris. A protective coating material should possess good bonding properties and flexibility under fan operating conditions since different flexibilities between the coating and the metal can also cause lining failure. Although many coating materials have been applied to protect blades from corrosion,[3,4] no coating material that provides both good bonding and flexibility for the impellers of a wet fan is presently available.

Care during welding and correct choice of materials are also important for wet-fan construction, since welds are very vulnerable to galvanic corrosion.

4.8.5 Existing Facilities

4.8.5.1 Cane Run Power Station--

Design information from this facility is the most complete. Flue gases from the existing boiler ID fans at Cane Run Unit 4 flow through ID booster fans into the scrubbing system. Guillotine isolation dampers are provided at the inlets of each of the two booster fans and at the outlet of each contactor module. The booster fans are needed to overcome the additional pressure drop caused by the contactor modules.

American Standard fluid drives permit the booster fans to follow boiler load; the booster fans will maintain a constant gas pressure to the scrubber and neutralize the additional pressure drop the scrubber system places on the existing ID fans. The booster fans are Buffalo Forge double-width, double-inlet units rated at 367,000 acfm at 325°F. The fan bearings are water-cooled, Dodge sleeve units. The fans have fluid drives driven by 1250-hp Reliance Electric induction motors rated at approximately 720 rpm. The fluid drives are American Standard, size No. 427, Class 4 units with No. 1004 shells and tube coolers. The coolers are water-to-oil, American Standard, type BCP heat exchangers. The fluid drive oil pump is a constant displacement gear pump.

Resistance temperature detectors on the fan, motor, and fluid drive bearings provide a signal to temperature monitors. Annunciator warning is set at 260°F.

A vibration element located on the fan outboard bearing provides input to a vibration monitor. Vibration in inches per second is read on the monitor. Contacts in the monitor provide annunciator warnings of high vibration (0.2 in./s) and for motor cutoff on excessive vibration (0.3 in./s). No scrubber fan problems have been reported.

4.8.5.2 Green River Power Station--

At Green River Power Station, the flue gases from each boiler are coupled into a series of mechanical collectors where primary particulate removal takes place. The flue gas is then drawn from the existing breeching through a guillotine-type isolation damper and associated ductwork by the scrubber fan. This fan is a Buffalo Forge double-inlet unit rated at 360,000 acfm at 300°F. It is constructed of mild steel and driven by a 1500-hp Allis Chalmer motor at 890 rpm. This fan generates a pressure of 18 in. H_2O and maintains a pressure of 0 in. H_2O upstream from the fan. This ensures that there is no back pressure on the boilers.

In an early operation, this fan was unbalanced and experienced excessive vibration, which required system shutdown for balancing.

4.8.5.3 Conesville Power Station--

Conesville Unit 5 has two air-foil type fans located after the ESP and before the scrubber. Guillotine dampers are provided at the inlets and outlets of the fans, and a louver damper permits a bypass.

The fans, from the Green Fuel Economizer Company, are rated at 850,000 acfm at 286°F. They are constructed of mild steel and driven by 7000-hp motors at 900 rpm. They generate pressures up to 46 in. H_2O.

This plant experienced occasional motor fluid coupling problems.

4.8.5.4 Paddy's Run Power Station--

Paddy's Run Unit 6 has two 1500-hp ID booster fans after the reheater, each having a 175,000 acfm capacity at 350°F. These fans had no operating problems; design details are not available.

4.8.5.5 Phillips Power Station--

The lime scrubbing FGD facility at Phillips Station is a two-stage venturi scrubber system (designed by Chemico Corp., N.Y.), one stage to remove particulates and the other stage to remove SO_2.[2-5] A wet-type fan was installed between the two scrubbers* handling about 500,000 acfm flue gas at 340°F. Sprays were provided to remove solids buildup on the fan blades and to wash off acids resulting from scrubber carryover.

The fan housings are lined with 1/4-in.-thick natural rubber. The wheel material is Carpenter 20 Cb 3, a special stainless steel containing niobium and tantalum. The fan shaft is 316L stainless steel. Each fan is driven by a 4160-V electric motor rated at 5500 hp at approximately 1200 rpm. A closed system supplies cooling water to the fan bearings.

The outlet gas temperature from the first-stage scrubber is normally in the 110° to 120°F range. At 175°F, a control valve automatically opens to admit emergency cooling water to the upper cone of the venturi. Additional temperature rise automatically shuts down the fan and closes the isolation dampers.

Many fan problems occurred during the trial run. The first problem was stress on the fan blades. In order to determine the condition of the fans, Structural Dynamics Research Corporation (SDRC) conducted a series of strain gauge tests. Its results indicated that the yield strength was exceeded in several portions of the fan blades and that a degree of metal deformation was taking place. After additional testing, SDRC recommended the installation of doubler (reinforcing) plates on each of the blades to reduce the stress to acceptable levels. After actual exposure tests with stress-welded specimens in the fan atmosphere, it was also recommended that the doubler plates be welded with Inconel 112 rod, rather than with rods of Carpenter 20, 4 NIA, or 8 N12, which were used earlier. Doubler plates were installed on all fans by the end of 1974 and the results were satisfactory.

---

* In the Chemico pilot-plant study, an ID fan was used downstream from the two scrubbers after a reheater. In the plant application, however, space limitation dictated the wet-type fan installation.

Frequent inspection of the fans revealed significant pitting attack under the fly ash/sludge deposits on the back of the fan blades and numerous cracks from chloride stress corrosion around the blade welding spots. Despite the addition of lime for SO_2 removal and pH control, the pH of the fan spray water dropped from about 6.5 to 2 across the fan. The spray water seemed to remove more SO_2 than was expected, turning spray water into acid mist. In a trial installation, caustic was added to the fan spray water, but because large quantities were required to obtain a pH of 4, the trial was terminated. Installation of six new Bete Fog type nozzles (No. TF16FC) ahead of the fan gave good results in removing deposits and reducing pitting attack on the blades.

At the recommendation of Franklin Institute Research Laboratory (Philadelphia, Pa.), the blades were coated with an epoxy-based, acid-resistant material, Coroline 505AB (Ceilcote Co., Berea, Ohio). During operation, the fan blades and the coating material experienced different stresses, resulting in the failure of the coating. Prospective fan coating materials were then tested by exposing coated test plates to the fan atmosphere. Those tested showed polyurethane rubber to be the most suitable coating, and one of the fan hubs was coated with that material for further testing. Bonding failure prevented a full evaluation.

Test specimens of Inconel 625 exposed to the fan atmosphere showed no indication of corrosion.

4.8.5.6 Bruce Mansfield Power Station--

The design of the Bruce Mansfield FGD system is similar to that of the Phillips system in that wet fans are installed between two-venturi scrubbers.[1] There are six fans in service, manufactured by Green Fuel Economizer Co. These are airfoil, radial-tip units rated at 558,000 acfm with a pressure of 75 in. H_2O at 118°F. They are driven by 13.2-kV electric motors rated at 9000 hp and 1300 rpm. The fan blades are made of Inconel and shafts are fabricated of carbon steel, clad with Carpenter 20. The carbon steel fan housing and scrolls are lined with rubber.

Problems were experienced with these fans due to high levels of acidity (pH of about 2) and rubber lining damage resulting from chips of scale being carried through the system.[6]

The exposed carbon steel corroded, and the fan scrolls were replaced with Inconel. Some pitting of the carbon steel hubs has also occurred as the result of seal leakage.

REFERENCES

1. Designing Large Central Stations to Meet Environmental Standards. Generation Planbook, 1976, pp. 25-34.

2. Isaacs, G.A. Survey of the Flue Gas Desulfurization System at the Phillips Power Station, Duquesne Light Company. EPA 68-02-01321, June 16, 1975.

3. Pernick, S.L., Jr., and R.G. Knight. Duquesne Light Co., Phillips Power Station Lime Scrubbing Facility. In: Environmental Protection Agency Flue Gas Desulfurization Symposium, Atlanta, November 4-7, 1974.

4. Pernick, S.L., Jr., and R.G. Knight. In: 69th Annual Meeting of APCA. Boston, June 15-20, 1975.

5. Pernick, S.L., Jr., and R.G. Knight. Duquesne Light Company, Elrama and Phillips Power Stations Lime Scrubbing Facilities. In: Environmental Protection Agency FGD Symposium, New Orleans, March 8-11, 1976.

6. Durkee, K.R. Survey of Pennsylvania Power's Bruce Mansfield Power Generating and Flue Gas Desulfurization System. Meeting Report, July 14, 1977.

BIBLIOGRAPHY

Steam/Its Generation and Use. Babcock & Wilcox Co., 38th edition, 1975.

CONTENTS

4.9 THICKENER/CLARIFIER

Page

4.9.1 Introduction 4.9-1

4.9.2 Service Description 4.9-3

- 4.9.2.1 Slurry pH 4.9-6
- 4.9.2.2 Calcium Sulfite and Sulfate Sludge Characteristics 4.9-6

4.9.3 Design Parameters 4.9-8

- 4.9.3.1 Mechanical Design 4.9-8
- 4.9.3.2 Use of Flocculant 4.9-17
- 4.9.3.3 Sizing Criteria 4.9-21

4.9.4 Materials of Construction 4.9-27

4.9.5 Operating Procedure 4.9-27

4.9.6 Existing Facilities 4.9-28

References 4.9-34

Bibliography 4.9-36

4.9 THICKENER/CLARIFIER

This section of the Lime FGD Systems Data Book presents design information on the thickener/clarifier. The scope of this section begins at the thickener/clarifier slurry feed piping and ends at the clarified overflow collection weir and the suction to the underflow sludge pumps.

4.9.1 Introduction

A thickener/clarifier is a sedimentation device that concentrates a slurry under gravity, so that the settled solids may be disposed of and the clarified liquid recycled. This process dates back to 1906.

The product of the sedimentation process usually dictates the terminology. When the primary object is to produce clear liquid from a dilute suspension, the process is called "clarification," and the unit is known as a "clarifier." When recovery of the settled solids in the form of a concentrated slurry is of prime importance, however, the terms "thickening" and "thickener" are commonly used. Although both these operations are equally important in lime scrubbing systems, the terms thickening and thickener are used in this discussion.

A general concept of sedimentation may be obtained by observing some finely divided solids in water in a graduated cylinder. At the start, the solids are uniformly dispersed throughout the cylinder [Figure 4.9-1(1)]. When the sedimentation process begins, solid particles begin to sink. The concentration in the top of the liquid decreases; that in the bottom increases. A concentration gradient forms and can be divided into the zones shown in Figure 4.9-1(2). Zone A is a clear supernatant. Zone B is the slurry zone. Zone C is a transitional phase between the slurry and the concentrated sludge, and Zone D is the sludge itself.

The solids in the second and third drawings settle at a constant rate and the sludge portion (Zone D) increases as the result of the accumulation of settled particles. The particles in Zone D continue a slow compaction. This zone is referred to as a "compression zone."

When the A-B interface finally joins the B-C interface (at the critical point), Zones B and C disappear [Figure 4.9-1(4)]. A further settling takes place through the "compaction" of the settled solids, the liquid being pressed out of the floc and out of the interstitial spaces between the floc [Figure 4.9-1(5)].

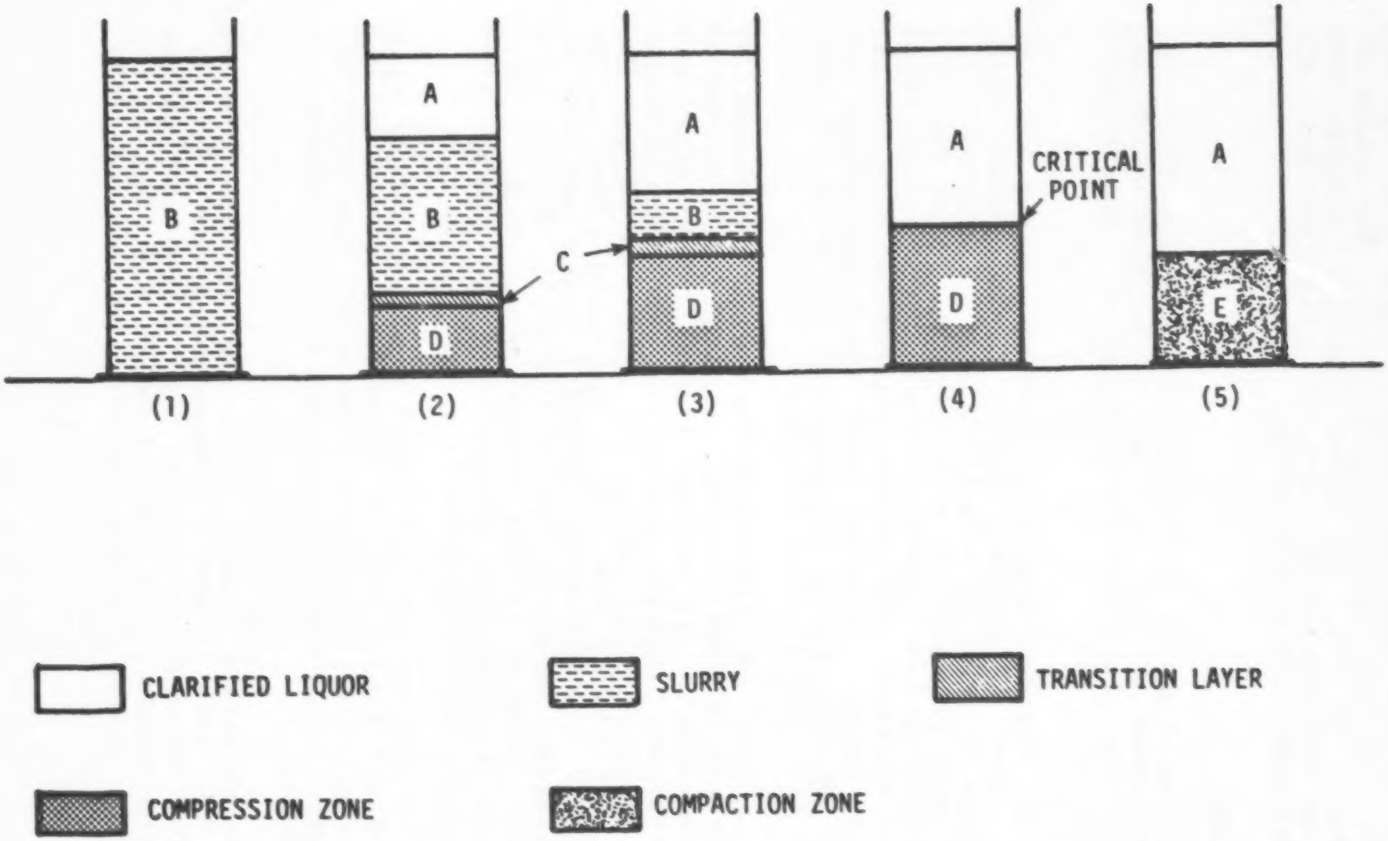

A
B
C
D
E
CRITICAL POINT
(1)
(2)
(3)
(4)
(5)
CLARIFIED LIQUOR
SLURRY
TRANSITION LAYER
COMPRESSION ZONE
COMPACTION ZONE

Figure 4.9-1. Sequence of sedimentation in a cylinder.

All the operations described take place in the thickener of a lime slurry scrubbing system. The degree of compression, compaction, and overflow clarification depends on design variables, particularly the surface areas and sidewall depth, which are discussed in this section.

4.9.2 Service Description

The most common type of thickener is circular in design with a center drive unit for a rake mechanism. This is the type used by lime scrubbing facilities and is described in this section. When space is limited, an alternative design called the high-capacity thickener may be used. The Lamella plate-type thickener is an example of this. It is used successfully in the phosphate industry. This type of thickener was tested at the Phillips Power Station and the TVA Shawnee facility.

A typical thickener (Figure 4.9-2) consists of a large circular holding tank with a central vertical shaft. The shaft is supported either by a center column or by a bridge (Figure 4.9-3). Two long, radial rake arms with the option of two short ones extend from the lower end of the vertical shaft. Plow blades are mounted on the arms at an oblique angle and have a clearance of 1.5 to 3 in. from the bottom of the tank. They can be arranged so that the bottom is swept either once or twice during each revolution. The bottom of the tank is usually at a grade of between 1:12 to 1.75:12 from the center. The settled sludge forms a blanket on the bottom of the thickener tank and is pushed gently toward the central discharge outlet. Center scrapers clear the discharge trench and move the solid deposits toward the underflow discharge point.

In normal operations, scrubber slurry is fed through the feedwell into the thickener at a concentration of 7 to 15 percent solids and at a rate of up to approximately 1000 gal/min, depending on tank size. The sludge is usually discharged as underflow at a concentration of 20 to 45 percent solids; if sulfate is the predominant species, the underflow may be as high as 60 percent solids.

The use of flocculant can reduce solids concentration in the thickener overflow, which would contain 50 to 100 ppm suspended solids without flocculant and 10 to 70 ppm with it. Higher feed solids concentration, however, will result in higher suspended solids in the overflow, which is returned to the scrubbing system for reuse.

In this application, the thickener has a diameter of 50 to 100 ft (though it could be as much as 300 to 400 ft), and a sidewall height from 8 to 14 ft.

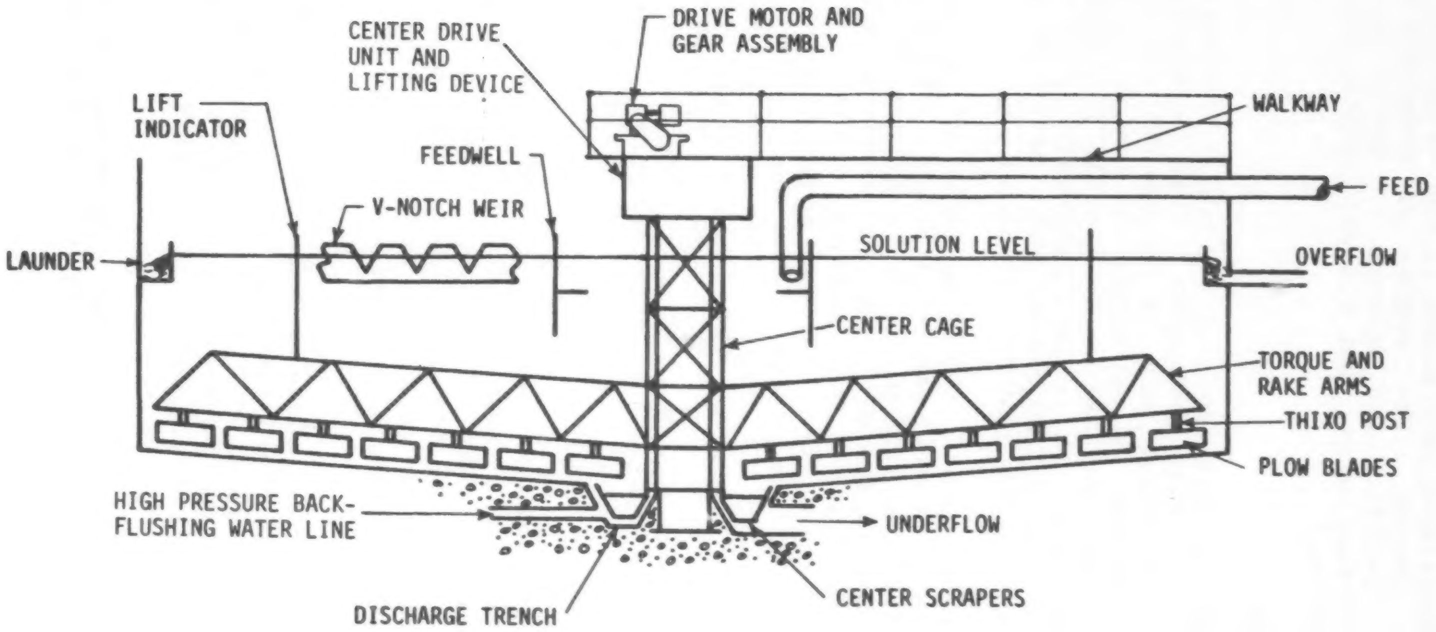
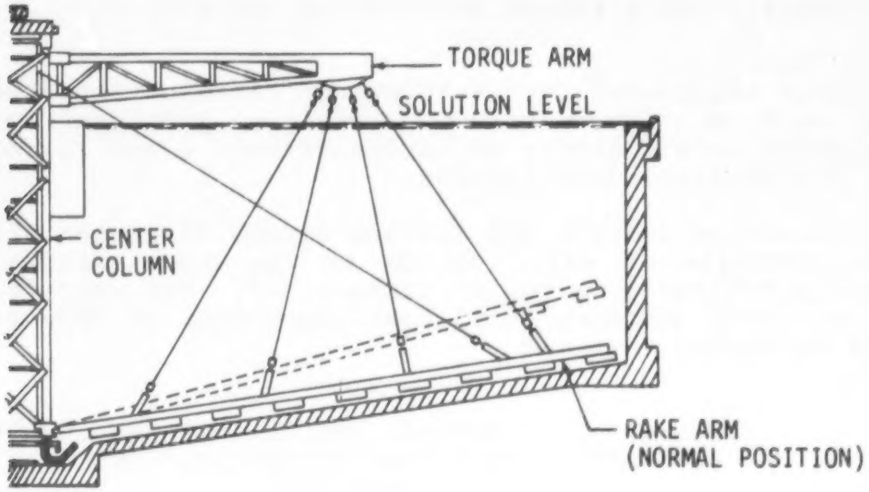
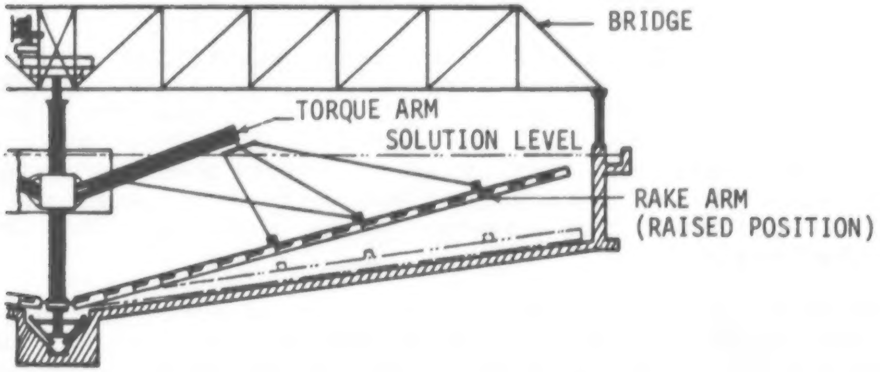

CENTER DRIVE UNIT AND LIFTING DEVICE
DRIVE MOTOR AND GEAR ASSEMBLY
LIFT INDICATOR
WALKWAY
FEEDWELL
FEED
V-NOTCH WEIR
LAUNDER
SOLUTION LEVEL
OVERFLOW
CENTER CAGE
TORQUE AND RAKE ARMS
THIXO POST
PLOW BLADES
HIGH PRESSURE BACK-FLUSHING WATER LINE
UNDERFLOW
DISCHARGE TRENCH
CENTER SCRAPERS

Figure 4.9-2. Thickener supported by a center column, with truss-type rake arms and Thixo post plow blades.


TORQUE ARM
SOLUTION LEVEL
CENTER COLUMN
RAKE ARM (NORMAL POSITION)

a) COLUMN-SUPPORTED CABLE TORQ THICKENER
(DORR-OLIVER, INC.)


BRIDGE
TORQUE ARM
SOLUTION LEVEL
RAKE ARM (RAISED POSITION)

b) BRIDGE-SUPPORTED SWING LIFT THICKENER
(EIMCO)

Figure 4.9-3. Hinged rod-type designs with two types of support structure.

The rake arms are driven by a 2- to 5-hp motor with a worm gear connection at a period of 10 to 20 rev/min.

4.9.2.1 Slurry pH--

Slurry introduced into a thickener contains dissolved ionic species such as calcium, sulfite, sulfate, hydrogen, hydroxide, and chloride ions. Slurry pH ranges between 4 and 11, according to the predominant ionic species.

4.9.2.2 Calcium Sulfite and Sulfate Sludge Characteristics--

An analysis of major solids in the waste sludge at the Conesville Station is given in Table 4.9-1. The sulfite/sulfate ratio can vary between facilities depending on the degree of sulfite oxidation.

Table 4.9-1. CHEMICAL ANALYSIS OF THE SLUDGE (DRY BASIS) OF A LIME-SCRUBBING SYSTEM (percent)

Fly ash	0.26
$CaSO_3 \cdot 1/2\ H_2O$	72.00
$CaSO_4 \cdot 2\ H_2O$	23.95
$CaCO_3$	3.53
$MgCO_3$	0.26
Total	100.00

Without forced oxidation and large quantities of excess air in the system, the scrubber slurry solids will tend to be mostly sulfite for high-sulfur coals. If, however, the plant practices forced oxidation, the sulfate species will predominate. Although some limestone facilities in the United States practice forced oxidation, the technique has only been employed in the lime FGD system at the Shawnee steam plant of the Tennessee Valley Authority.[1]

Calcium sulfite crystals occur as extremely thin, fragile platelets about 10 to 100 μm across and 0.1 to 0.5 μm thick (Figure 4.9-4). They usually appear in clusters, or "rosettes," which are stronger than single crystals. The clusters can be composed of as few as 5 to as many as 100 or more platelets. They form an open structure, with water filling the voids. As a result, sulfite sludge is not as easily compacted by settling as sulfate sludge and typically generates a 35 percent solids underflow. The water retention of sludges containing sulfite, as well as the crystalline structure, results in thixotropic behavior. When shear force is applied, thixotropic material

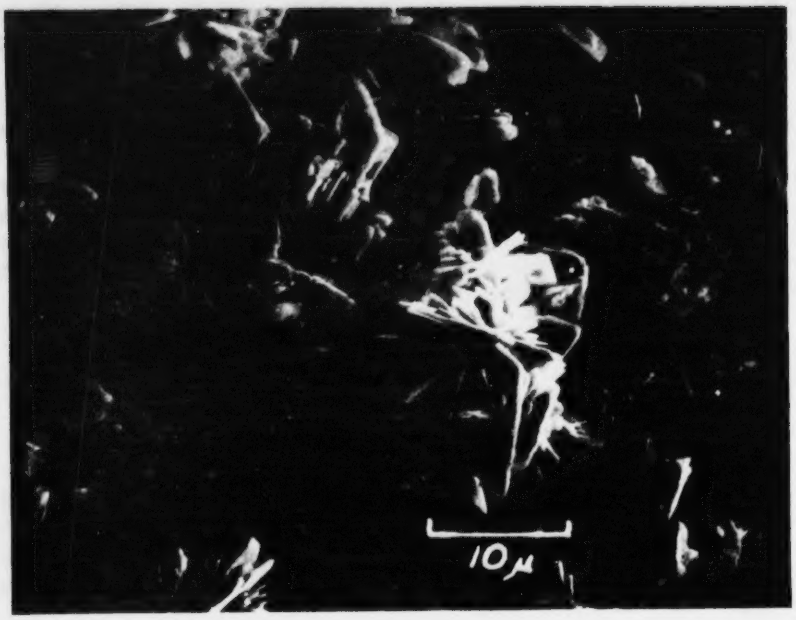


Figure 4.9-4. Calcium sulfite sludge.

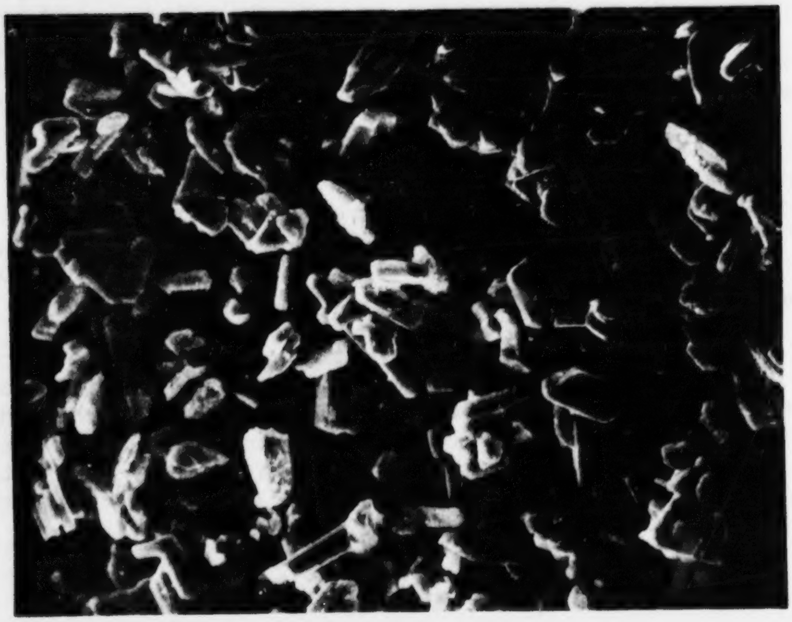


Figure 4.9-5. Calcium sulfate sludge.

Source: Dravo Corp.

becomes less viscous and flows readily. It should be noted, however, that the term "thixotropic" is not used accurately here, since thixotropic materials become stable when the shearing force is removed. Flue gas desulfurization sludges tend to remain in the liquid-plastic form.

The crystalline structure of calcium sulfate is diamond or rhomboid shaped (Figure 4.9-5) and varies in size from 1 to 100 μm along each edge. Calcium sulfate crystals have better settling and dewatering characteristics compared with sulfite crystals. They retain less water and, as a result, high-sulfate sludges (having more than 60 percent sulfate) are nonthixotropic and will settle rapidly to produce up to 60 percent solids underflow.

4.9.3 Design Parameters

A thickener consists of several pieces, not all of which are supplied by all thickener vendors. Parts that are normally purchased from thickener vendors include the center drive unit, torque control and alarm system, rake arm mechanism, lifting device, lift indicator, feedwell and internal piping, anchorage ring or bottom flange for structures with center-column support, and the walkway.

Vendors also provide design specifications. They are not, however, normally responsible for the design and construction of the tank, nor do they provide items such as external piping, the electrical conduit and wiring, weirs, baffles, and overflow launders. The walkway beam supplied by thickener vendors is usually designed to carry only the walkway itself, live loads, and the handrail. Additional weight for piping or external equipment is excluded.

4.9.3.1 Mechanical Design--

The major components of a thickener include the center drive unit, feedwell, rake arm mechanism, and flow arrangements. Design considerations for components and associated auxiliary equipment are discussed in this section.

Center drive unit--The center drive unit is the workhorse of the rotating rake arm mechanism. Choosing the right one from several available designs depends on the size of the thickener and the torque requirements of the thickened solids. The center drive unit consists of a primary worm gear motor, an intermediate worm gear reduction box with torque control and alarm system, and a main spur gear (Figure 4.9-6).

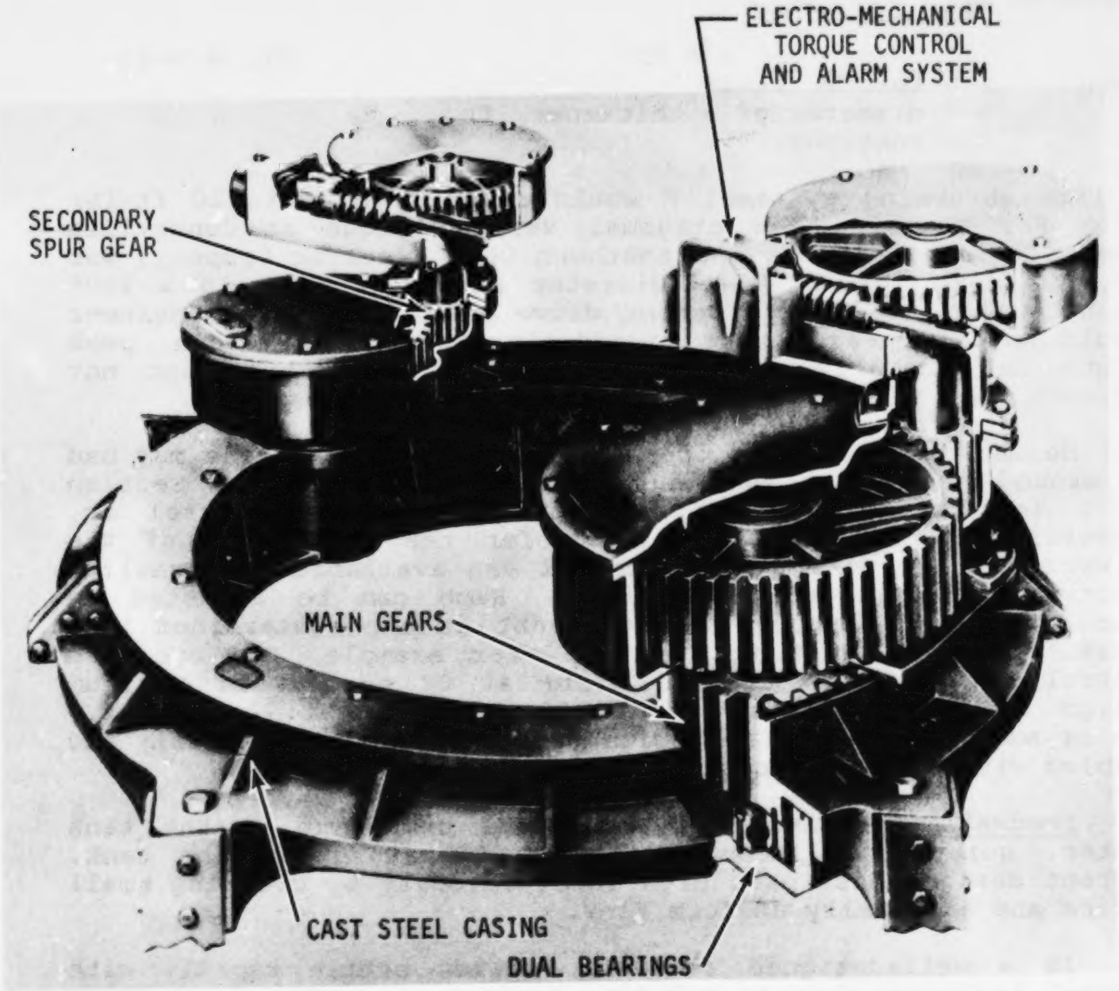

ELECTRO-MECHANICAL TORQUE CONTROL AND ALARM SYSTEM
SECONDARY SPUR GEAR
MAIN GEARS
CAST STEEL CASING
DUAL BEARINGS

Figure 4.9-6. Center drive unit (EIMCO).

When the rake arms stir the sludge, it resists the movement and the torque is transferred to the center drive unit. The normal running torque requirement of a thickener is empirically expressed as:

$$\tau = KD^2 \qquad \text{(Eq. 4.9-1)}$$

where τ = torque, ft-lb
D = diameter of a thickener, ft.
K = constant.

In lime scrubbing systems, K would range from 15 to 20 ft-lb/ft^2. For example, the original design torque at Conesville Power Station (Columbus and Southern Ohio Electric Company) was 150,000 ft-lb for a 100-ft-diameter thickener ($\tau = 15 \times 100^2$ ft-lb). When ordering a center drive unit, the design engineer should specify peak torque in addition to running torque; peak torque is generally twice the running torque, but must not approach the yield strength of the metal.

During the thickener operation, the settled solids may bed in around the rakes and cause excessive torque (see Section 4.9.5 for further details). A torque overload control is, therefore, an important auxiliary for the protection of the drive unit. Three types of control are available: hydraulic, electromechanical, and electrical. Each can be adjusted to sound an alarm and stop the equipment at a predetermined load limit.[2] At the Cane Run Station, for example, the overload control sets off an audible alarm at 80 percent of maximum design running torque and cuts off the motor at 90 percent.[3] One or more torque control units can be used simultaneously and coupled with a visual torque readout.

Feedwell--The feedwell, a crucial component in the tank center, quiets the incoming flow before it enters the tank. Current designs dissipate high inlet velocity by creating small eddies and a radially uniform flow.

In a well-designed feedwell, solids settle rapidly with minimal influence from turbulence.

Rake arm mechanism--The main function of the rake arms is to move the settled solids to a central discharge point. Bridge-supported and column-supported designs generally employ two long arms with the option of two short ones, the latter added when necessary to rake the inner area.

Rake arms must be strong enough for the required torque, although their design also depends on the nature of the solids. They come in two main types: a truss-type and a rod-type.

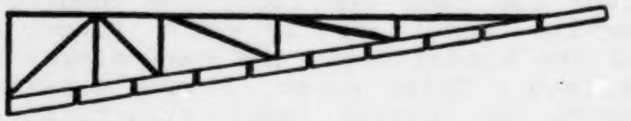
The truss-type arm is a conventional design (Figure 4.9-7a) that also acts as a torque arm. It is either bolted or welded to the center column and turned by a center drive unit. Blades are bolted to the bottom chord of the truss structure. When lime-generated sludges reach high density and high viscosity, the blades and the rake arm structure tend to form the sludge into an immobile "donut" or "island." Proper blade angles and extension of the blades below the raking arms by means of vertical posts (e.g., Thixo posts, Figure 4.9-7b) help eliminate this phenomenon by leaving fewer structural members to move through the sludge in the critical center area. In larger thickeners (300- to 400-ft diameter), the center depth would be excessive if a single slope were employed. The double sloping design (Figure 4.9-7c) eliminates this problem. This design leaves the truss somewhat above the thickest sludge, which forms near the center of the tank.

The rod type of rake arm has a hinged design (Figure 4.9-3). The arm is simply a long pipe pivoted at the center column either by a single tilted pin (Swing Lift, EIMCO) or by two pins, one horizontal and one vertical (Cable Torq, Dorr-Oliver). The rake arms are suspended and dragged by cables from torque arms, which rotate 30 to 45 degrees ahead of them. The interesting feature of this design is that the pivot pins allow the rake arms to swing over heavy deposits of coarse material. This design has further advantages over the truss-type in that it also offers lighter dead load, less drag, and less tendency for scale buildup in the rake arms. Heavy deposits, however, usually occur near the center of the thickener, and only a minimum amount of improvement is experienced at this point whatever the type of construction.

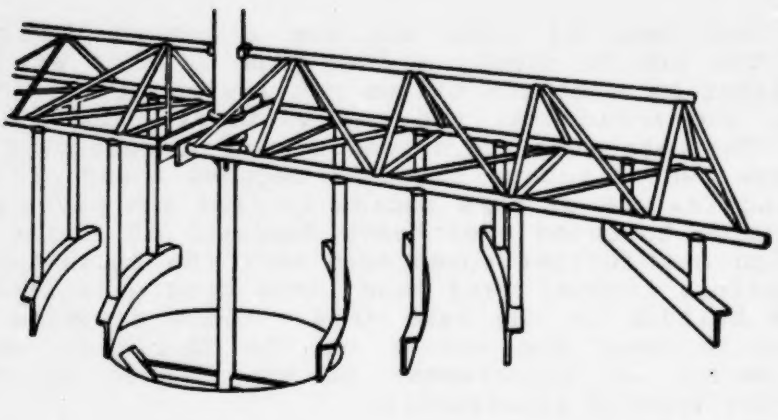
The size of the rod-type thickener is limited to 150 ft, since even a small lifting action near the center creates excessive swing at the tip of the rake arms. The lack of positive control of the lifting and lowering action is another problem with this design.

Lifting device--Truss-type thickeners are installed with some type of device for lifting the arm. This device permits continuous operation without excessive torque by lifting the rakes over coarse, settled solids and lowering them as these solids are removed. Hinged rake arm designs do not require a separate lifting device, because of the unique design mentioned earlier. It should be noted, however, that this design does not have positive control of the lifting action.

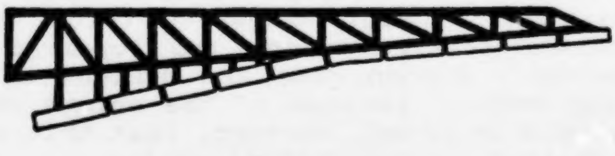
The truss type of lift can be activated automatically by the torque encountered by the arms, either by means of an ammeter on the mechanism drive motor, or by a mechanical torque indicator. When excessive torque is experienced, the entire



(a) CONVENTIONAL DESIGN



(b) THIXO POST DESIGN



(c) DOUBLE SLOPE DESIGN

Figure 4.9-7. Plow blade designs shown with truss-type rake arms.

mechanism is raised evenly. One lift of this type is shown in Figure 4.9-8. Lifting devices have been employed with up to 5 ft of lift, although 1 ft to 2 ft is more common. Indicators show the degree of arm lifting (Figure 4.9-2). Some vendors also offer a lift height sensing device for remote indication of rake arm location.

Flow arrangements--In a thickener, the three primary flow arrangements are as follows:

(A) Feed - Slurry suspensions are usually fed to the tank through a pipe under the walkway (Figure 4.9-2). In some designs, the influent pipe runs under the tank and the feed enters through the center column (Figure 4.9-9).

(B) Overflow - Clarified effluent is usually handled by a peripheral launder at the upper tank edge. V-notch overflow weirs help to distribute the internal flow patterns evenly within the tank (Figure 4.9-2).

(C) Underflow - Buried or inaccessible sludge lines incur the lowest installation cost of all underflow arrangements. Usually several of these lines are installed (vendors recommend a minimum of two), with one kept as a spare in case of plugging. A high-pressure water or air line should be available to clear the plugging.

One underflow design consists of a tunnel (Figure 4.9-9) to allow complete accessibility to the discharge point, valves, and associated piping. Although the most costly approach, it handles the maximum underflow solids concentrations with minimum maintenance problems.

Center-column pumping (Figure 4.9-10) lowers installation costs and can be used where ground conditions preclude a tunnel. Outlet pipes from the discharge trench end in one central vertical pipe, which passes up inside the center column, along the walkway, to a pump situated outside the tank perimeter (Figure 4.9-10a). A similar system (Figure 4.9-10b) consists of a double pipe, which permits removal of the inner pipe for cleaning. Another system has a submersible pump near the bottom of the center column (Figure 4.9-10c). With this arrangement, long suction lines are avoided, and underflow concentrations approaching those of the tunnel system can be handled. Although it is more expensive, the system will pump higher solids concentrations with less probability of plugging or loss of prime. In the column pumping operation, however, spare pumps and a pump hoist are recommended.

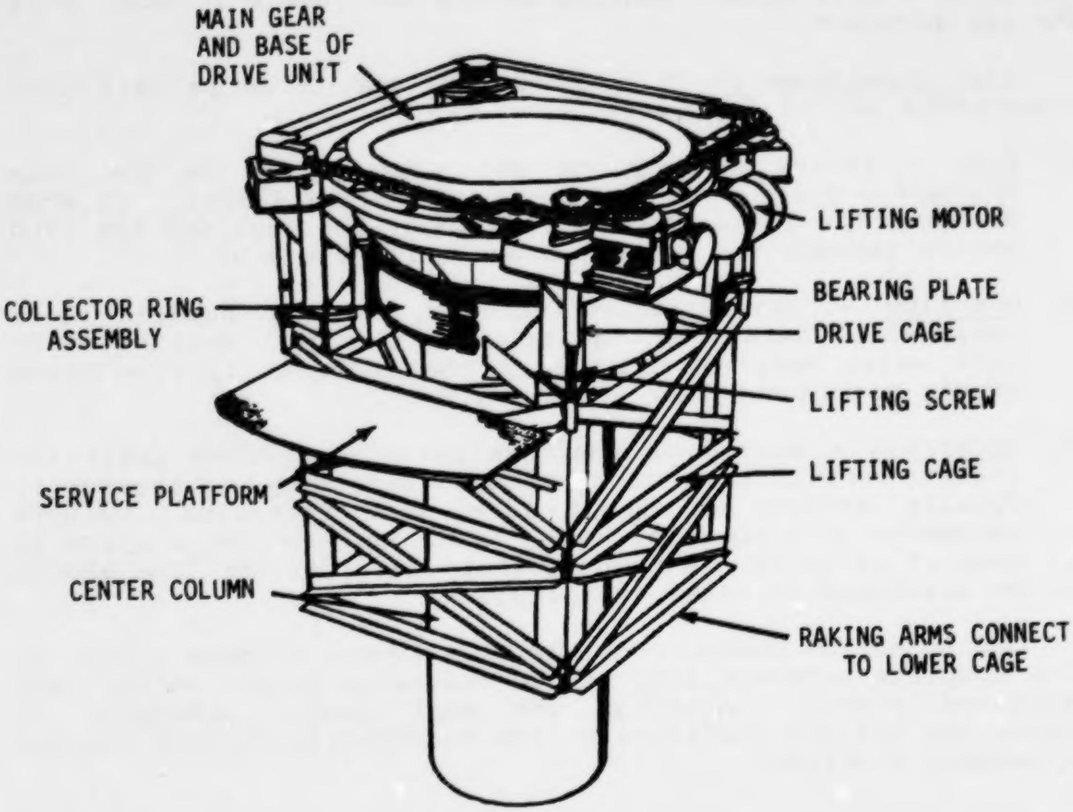

MAIN GEAR AND BASE OF DRIVE UNIT
LIFTING MOTOR
BEARING PLATE
COLLECTOR RING ASSEMBLY
DRIVE CAGE
LIFTING SCREW
LIFTING CAGE
SERVICE PLATFORM
CENTER COLUMN
RAKING ARMS CONNECT TO LOWER CAGE

Figure 4.9-8. Positive lifting device used on column-supported thickeners.

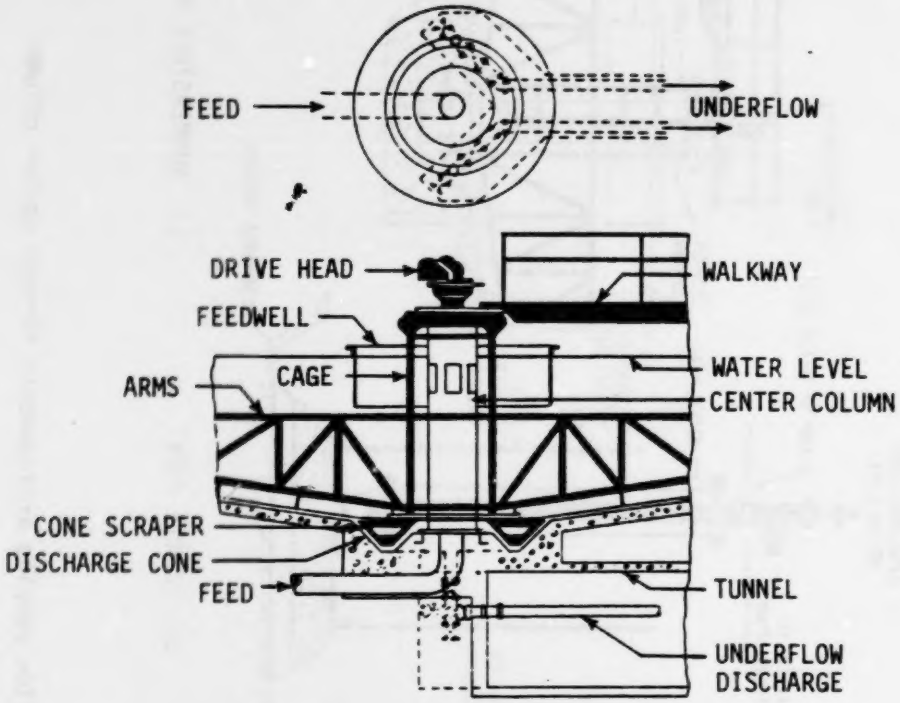
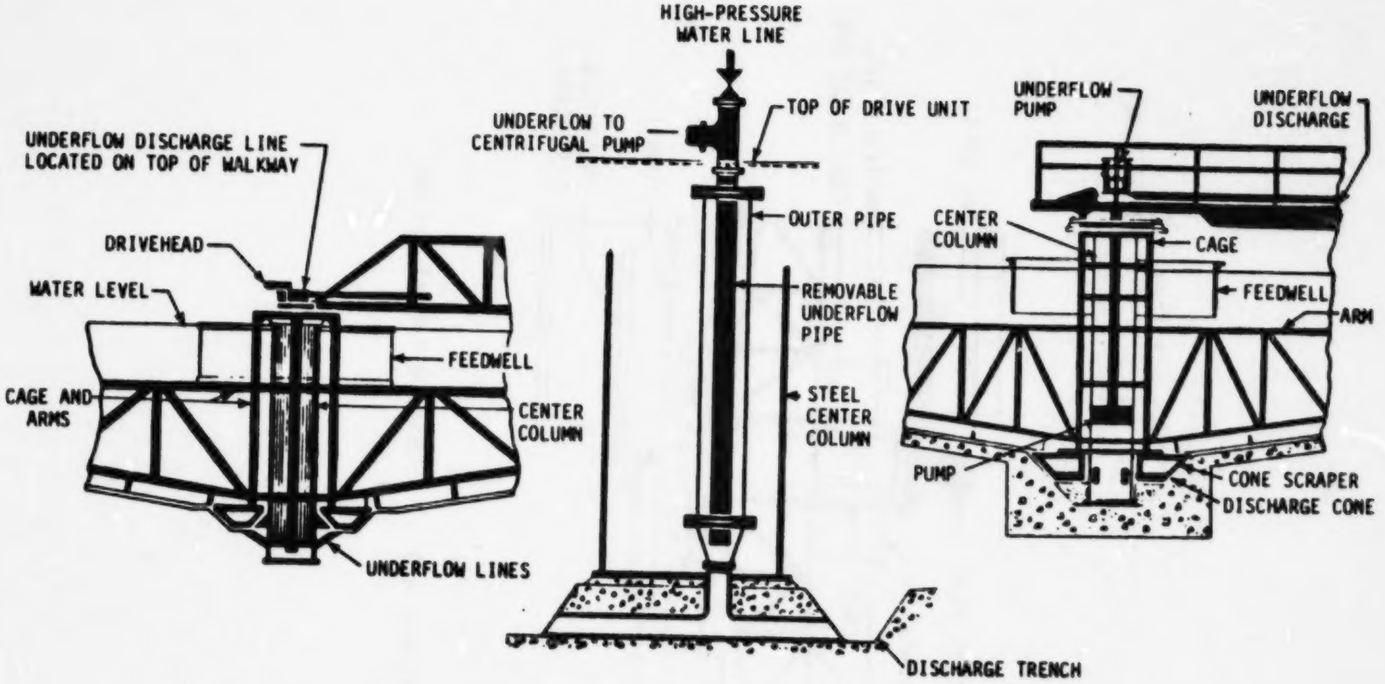

FEED
UNDERFLOW
DRIVE HEAD
WALKWAY
FEEDWELL
WATER LEVEL
CAGE
ARMS
CENTER COLUMN
CONE SCRAPER
DISCHARGE CONE
FEED
TUNNEL
UNDERFLOW
DISCHARGE

Figure 4.9-9. Standard tunnel system.


HIGH-PRESSURE WATER LINE
UNDERFLOW TO CENTRIFUGAL PUMP
TOP OF DRIVE UNIT
UNDERFLOW DISCHARGE LINE LOCATED ON TOP OF WALKWAY
DRIVEHEAD
WATER LEVEL
FEEDWELL
CAGE AND ARMS
CENTER COLUMN
UNDERFLOW LINES
OUTER PIPE
REMOVABLE UNDERFLOW PIPE
STEEL CENTER COLUMN
DISCHARGE TRENCH
UNDERFLOW PUMP
UNDERFLOW DISCHARGE
CENTER COLUMN
CAGE
FEEDWELL
ARM
PUMP
CONE SCRAPER
DISCHARGE CONE

a) SINGLE PIPE

b) DOUBLE PIPE

c) SUBMERSIBLE PUMP

Figure 4.9-10. Underflow pumping arrangements through center column.

4.9.3.2 Use of Flocculant--

Many of the solid particles in the slurry are dispersed as a stable colloidal sol. Because the particles are so small (Table 4.9-2), their surface area is large in relation to their mass. As a result, surface phenomena predominate and control the behavior of the sol.[4,5]

Table 4.9-2. TYPICAL SIZE DISTRIBUTION OF A LIME-GENERATED SLUDGE

Equivalent spherical diameter, μm	Cumulative wt. percent
+18	10
-18	90
-12	80
- 9	70
- 8	60
- 6.4	50
- 5	40
- 4	30
- 3	20
- 1.5	10

There are two types of colloidal sols, lyophobic and lyophilic. Their properties are listed in Table 4.9-3. Colloidal sols formed in FGD systems are usually lyophobic and in the subsequent text only these sols will be discussed.

"Stability" refers to the inherent property of colloidal particles to remain dispersed despite passage of time; whereas "instability" describes the tendency of particles to coalesce whenever particle-to-particle contact is made.

The stability of particles in the sol is due largely to the phenomenon of the electrical double layer, consisting of a charged-particle surface and a surrounding sheath of oppositely charged ions. Several theories have been advanced to describe quantitatively the concept of the electrical double layer. Helmholtz proposed this first in 1879; it was subsequently modified by a number of workers. In its simplest form, the theory states that particles in a colloidal sol have electrical charges on their surfaces.

The charge on all particles in a given dispersion is the same (either positive or negative) but can vary considerably in magnitude. It depends on the nature of the colloidal material.

The electrical double layers around particles inhibit their close approach to each other. In this way the double layers

Table 4.9-3. SUMMARY OF THE CHARACTERISTIC DIFFERENCES BETWEEN THE TWO CLASSES OF COLLOIDS.[6]

Lyophobic (No affinity for solvent)	Lyophilic (Considerable affinity for solvent)
Low viscosity.	High viscosity.
Normally irreversible.	Reversible, i.e. will become colloidal again, after coagulation, on addition of solvent.
Particles show Tyndall effect, i.e., easily detected by ultramicroscope.	Particles not easily detected.
Particles are all positively or all negatively charged, i.e., they move in one direction under influence of applied electromotive force.	Particles move in both directions or not at all.
Particles coagulate and are precipitated on addition of electrolyte.	No precipitation by electrolyte unless added in large quantities, when "salting out" may occur. Give protection to lyophobic colloids from precipitating effect of electrolytes.
Examples:	Examples:
Metals, sulphur, metal sulphides, hydroxides ($Fe(OH)_3$,$Al(OH)_3$).	Starch, gum, soaps, haemoglobin, egg albumin, gelatin, agar agar; i.e., organic substances of high molecular weight.

confer stability to the sol. This property inhibits precipitation of solid particles, and the settling velocity is often too low to design an economical thickener with good overflow quality. It is necessary, therefore, to destabilize colloidal sols by reducing the forces that keep the particles apart (coagulation), and agglomerating the small particles into larger aggregates (flocculation), which have the settling velocities required to be practical. This is done by adding chemical conditioners to the colloidal sols.

Inorganic metal salts and polymers are among the chemicals that can be used for conditioning. The Hardy-Schulze Law states that the coagulating power of an electrolyte depends on its valency. Thus, soluble ferric or aluminum compounds (3-valent) are better coagulants than soluble ferrous compounds (2-valent) and far much better than 1-valent compounds.

Both inorganic and polymer conditioners agglomerate fine particles by neutralizing surface charges, thereby accelerating settling, and clarifying thickener overflow.

Polymers possess less neutralizing power but a higher capacity for "bridging" (simultaneous attachment) to two or more solid particles than do inorganic coagulants. They also provide the advantage of a very large increase in the size of the floc, which greatly increases their settling rate. Dorr-Oliver Laboratories (Stanford, Connecticut) performed a series of settling tests to study the effect of polymer dosage.[7] Figure 4.9-11 shows that the rate is increased 7 to 20 times, depending on polymer dosage.

Flocculation, however, yields a more dilute underflow (25 to 35% solids from lime-generated slurry) because of the bound water in the interstitial structure of the polymers. The correct polymer dose should be determined by trial-and-error through electrical potential measurement (zeta potential) and jar tests,[8] since an incorrect dose may cause side effects such as increased overflow turbidity, slower settling rate, or underflow plugging.

In general, a thickener using polymers need only be a third or half as large as one without flocculation.

Most polymers are bought in powder form and may be stocked for use at strengths of 0.5 to 1 percent. Stock solutions may be prepared as infrequently as twice a week, but they are usually made fresh every day and, in some cases, once per shift. The solution preparation system includes a manual or automatic blending system in which polymer is dispensed by hand or by a dry feeder.

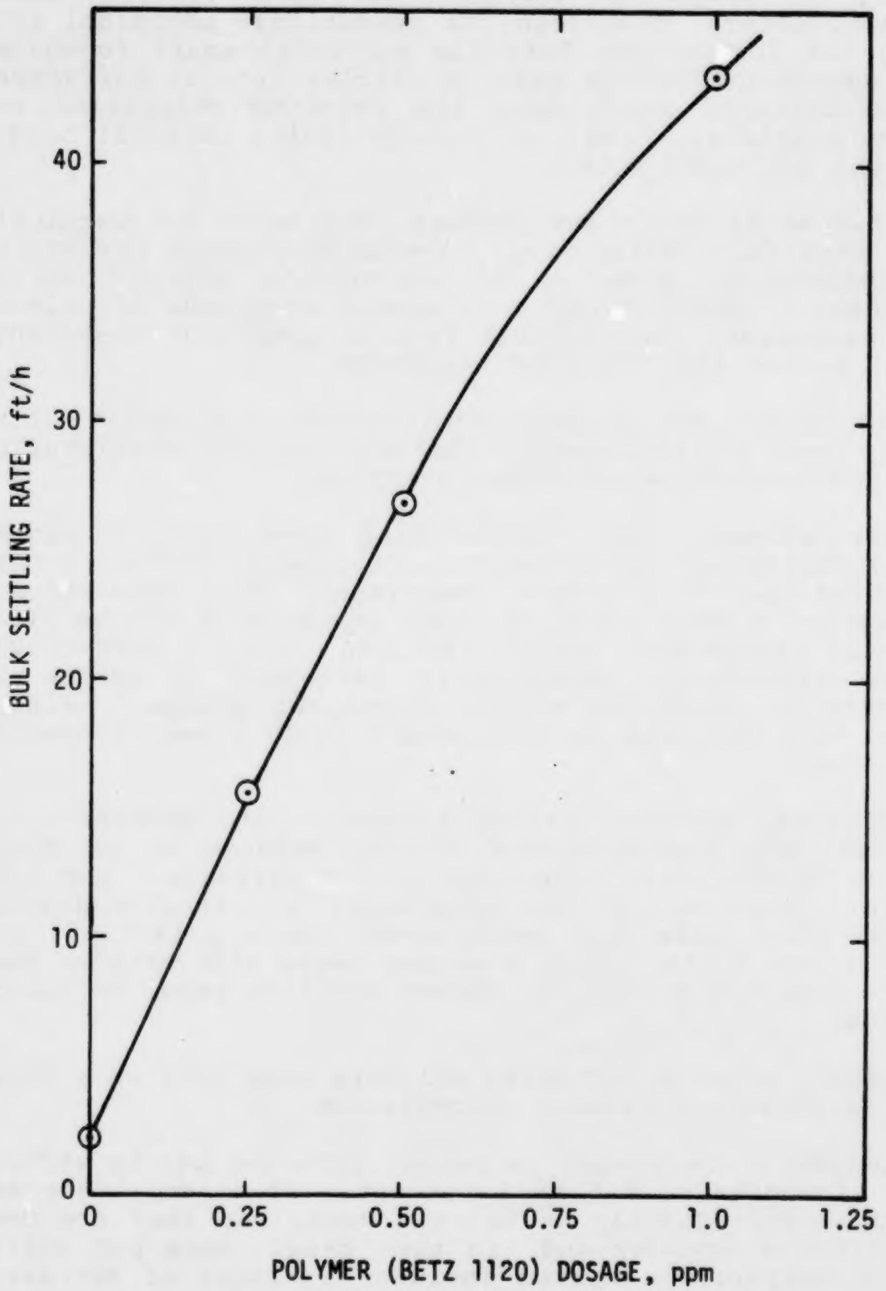


Figure 4.9-11. Effect on polymer on settling rate of lime-generated sludge.

Source: Dorr-Oliver

A schematic of a typical automatic dry feed system is presented in Figure 4.9-12. At Cane Run Power Station, a Pennwalt dual tank polyelectrolyte feeding system adds Betz 1100 Polyfloc to the thickener tank in a 0.5 percent solution.[9]

This system consists of a reciprocating screw feeder that has an adjustable stroke and operates at constant speed. It volumetrically meters dry polymer into two stainless steel wetting cones. These cones are provided with washdown water at controlled pressure and each one is connected to a small, high-velocity stream eductor in which the particles are individually wetted and dispersed. The combined discharge is passed to an open cylindrical tank, equipped with level controls and a slow-speed propeller mixer in which blending is completed. All water for the preparation process passes through a Varea-Meter so that an accurate water-to-polymer ratio may be set. The blended polymer requires a 15- to 30-minute aging period, because polymer chains in the dry product tighten like a wound spring and need time to unwind in the solution. When aging is complete, the slow-speed mixer is stopped and the batch awaits a demand signal, which depends on the need of the metering tank.

The aged polymer solution is metered by a diaphragm pump. As this pump lowers the level in the metering tank, a level control switch is actuated. This initiates the operation of a screw-type transfer pump, which withdraws solution from the aging tank and refills the metering tank. A signal that the level in the aging tank is low begins preparation for another batch, and the cycle is repeated.

Because viscous polymer solutions require dilution before application to processes, the system is provided with a second Varea-Meter and a valve so that dilution water flow may be observed and controlled. The metering pump discharge connects into the dilution water line and mixing occurs en route to the point of application.

Controls are mounted in a steel cabinet at one end of the system platform. An interlock prevents operation of the transfer pump until the batch has aged.

4.9.3.3 Sizing Criteria--

This section describes methods of determining the surface area and the side water depth of a thickener.

Surface area--One method of determining the surface area of a thickener is to use the result of a laboratory settling test with a representative sample of slurry. The characteristics of a slurry cannot be predicted, however, because quality varies greatly from plant to plant, as do ash content and chemical

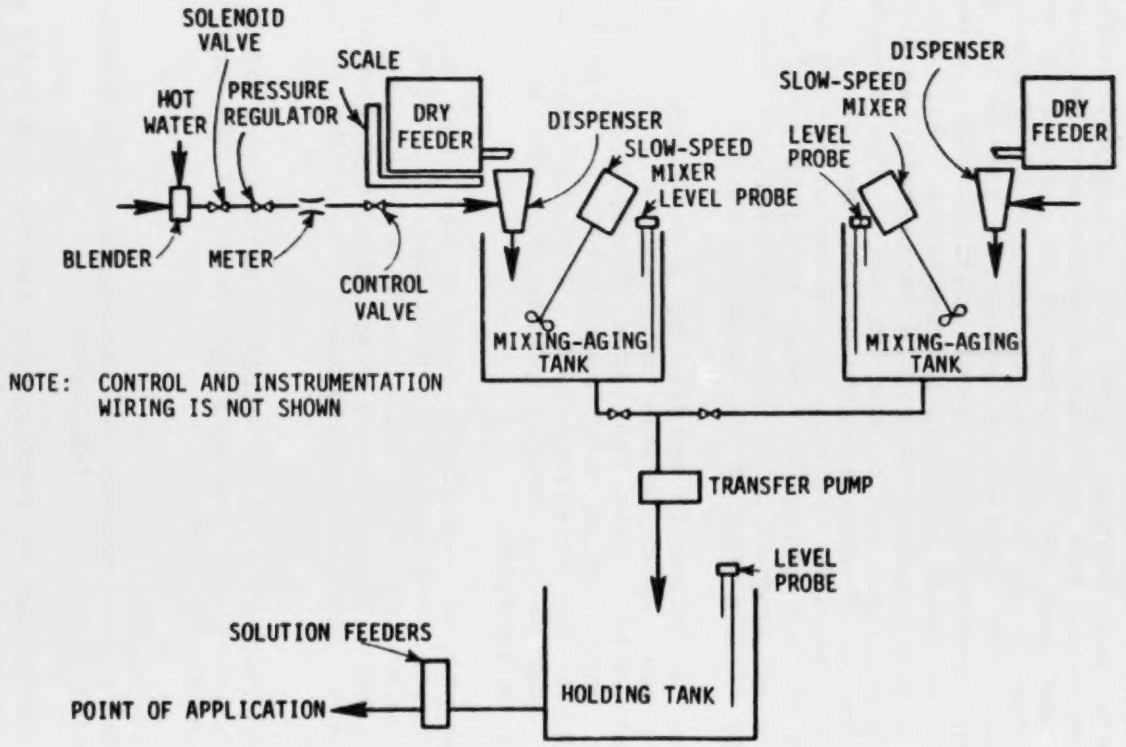

SOLENOID VALVE
HOT WATER
PRESSURE REGULATOR
SCALE
DRY FEEDER
DISPENSER
SLOW-SPEED MIXER
LEVEL PROBE
BLENDER
METER
CONTROL VALVE
MIXING-AGING TANK
NOTE: CONTROL AND INSTRUMENTATION WIRING IS NOT SHOWN
DISPENSER
SLOW-SPEED MIXER
LEVEL PROBE
DRY FEEDER
MIXING-AGING TANK
TRANSFER PUMP
LEVEL PROBE
SOLUTION FEEDERS
HOLDING TANK
POINT OF APPLICATION

Figure 4.9-12. Typical automatic dry polymer feed system.

constituents. Because of this, an empirical method is frequently used in designing a thickener for a new plant.

(A) Method I - If a representative slurry sample is available, a settling test can be performed as follows: a column is filled with a suspension of solids of uniform concentration (C_o) to height (H_o). Figure 4.9-13 shows the position of the interface as the suspension settles. The rate at which the interface is subsiding at any given time is then equal to the slope of the curve at that time. When flocculation is used, polymers can be tested to determine the type and dosage.

The space required by the thickener can be determined by several techniques using the settling curve. One technique is the direct calculation technique, i.e., direct calculation of the unit area from a point on the curve in the following equation:

$$A = \frac{t_u}{C_o H_o} \qquad \text{(Eq. 4.9-2)}$$

where A = unit area, ft²/ton per day of dry solids
C_o = initial concentration, tons dry solids/ft³
H_o = initial height of solid suspension in the column, ft
t_u = time, days required for the interface to reach the height (H_u), under which the average concentration is the same as the desired underflow solids concentration (C_u).

Since $H_o C_o = H_u C_u$ (Eq. 4.9-3)

t_u is obtained from the settling curve at $H = H_u$. When C is expressed in weight percent, Equation 4.9-3 becomes:

$$C'_o H_o \rho_o = C'_u H_u \rho_u \qquad \text{(Eq. 4.9-4)}$$

where C'_o; C'_u = weight percent of feed and underflow solids concentrations

ρ'_o; ρ'_u = density of feed and underflow, tons/ft³, or g/cm³

Rearranging Equation 4.9-4, H_u becomes:

$$H_u = \frac{C'_o H_o \rho_o}{C'_u \rho_u \;{}_u} \qquad \text{(Eq. 4.9-5)}$$

Figure 4.9-13 presents the result of a settling test made by EIMCO on a slurry sample from Bruce Mansfield plant. For this sample, H_o = 1.45 ft, ρ_o = 1.0386 g/cm³, ρ_u = 1.206 g/cm³, C'_o = 6.7 wt.%, and $C'_u \cong$ 30 wt. %. Substituting these values in Equation 4.9-4:

$$H_u = \frac{6.7 \text{ wt. \% } \times 1.45 \text{ ft } \times 1.0386}{30 \text{ wt. \% } \times 1.206}$$

$$= 0.279 \text{ ft}$$

From Figure 4.9-13, t_u is 104 min (or 0.0722 day). Since the feed concentration, C_o, is 0.002172 ton dry solids/ft³, the thickener area from Equation 4.9-2 becomes:

$$A = \frac{t_u}{C_o \; H_o}$$

$$= \frac{0.0722 \text{ day}}{0.002172 \text{ ton/ft}^3 \times 1.45 \text{ ft}}$$

$$= 22.93 \text{ ft}^2\text{/ton per day of dry solids}$$

A variation of this technique has been modeled by Kynch and modified by Talmadge and Fitch for suspensions with hindered settling characteristics.[10,11] The thickener area is expressed as:

$$A' = \frac{Q \; t_x}{H_o} \qquad \text{(Eq. 4.9-6)}$$

where A' = unit area, ft²

Q = volumetric flow rate, ft³/day

t_x = time in days required for the interface to reach the height (H_u) under which the average concentration is the same as the desired underflow solids concentration, (C_u).

Since the feed solids concentration is C_o ton per ft³, the solid loading Q' is

$$Q' \text{ (tons/day)} = Q \times C_o \qquad \text{(Eq 4.9-7)}$$

or

$$Q = \frac{Q'}{C_o}$$

Rearranging Equations 4.9-6 and 4.9-7 yields

$$A = \frac{A'}{Q'} = \frac{t_x}{C_o \; H_o} \text{ ft}^2\text{/ton per day of dry solids} \qquad \text{(Eq. 4.9-8)}$$

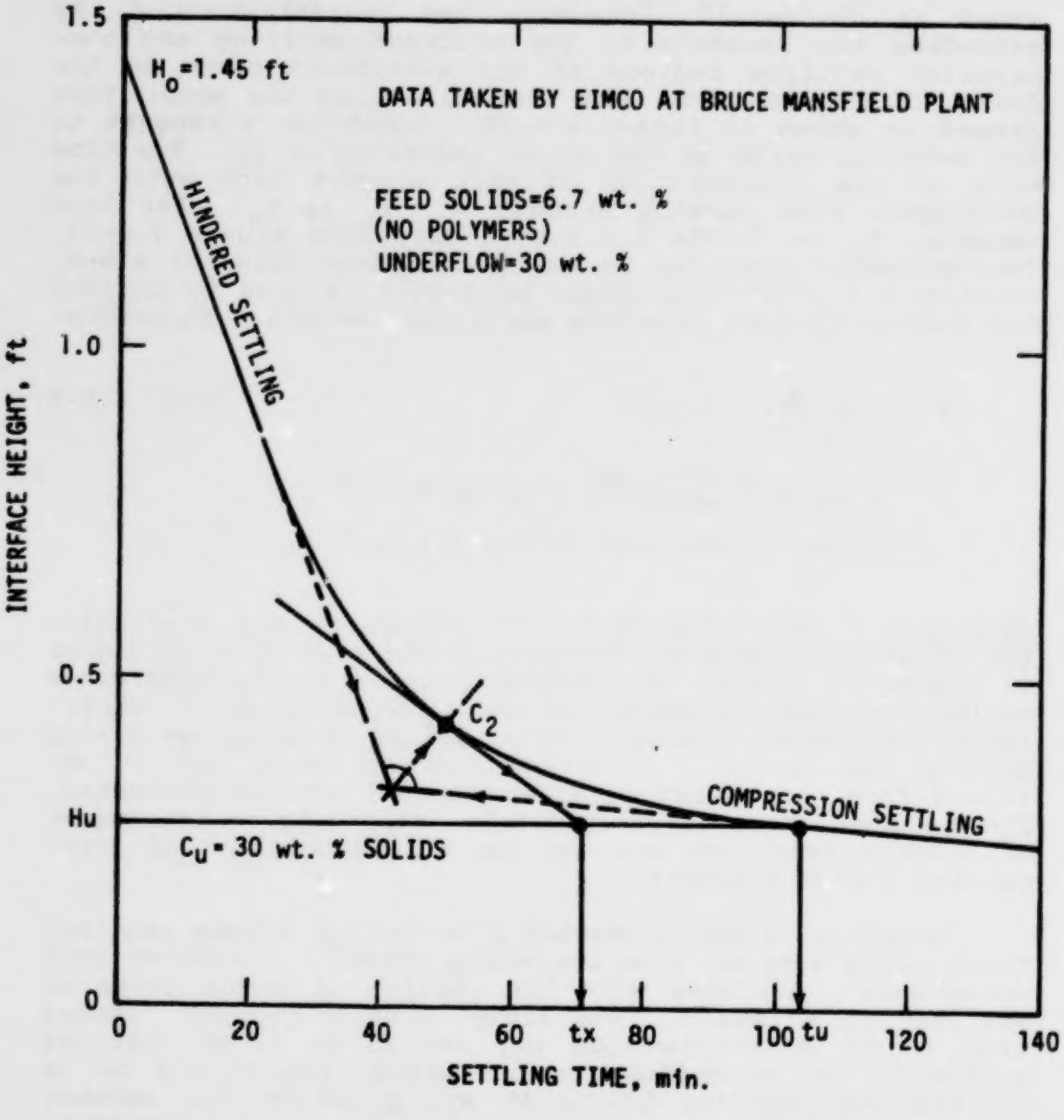


Figure 4.9-13. Graphical analysis of interface settling curve.

The main difference between the two techniques is in determining the settling time. The time, t_x, can be determined as follows:[12] Determine the concentration C_2 by extending the tangents to the hindered settling and compression settling regions of the subsidence curve to the point of intersection, and then bisecting the angle thus formed as shown in Figure 4.9-13. Construct a tangent to the settling curve at the point indicated by C_2. The time axis of the intersection of this tangent line with the horizontal line passing through $H = H_u$ is t_x. For this example, t_x is 71 min (or 0.0493 day) from Figure 4.9-13. The thickener area can be calculated from Equation 4.9-8. Usually a 1.25 to 1.33 scale-up factor is used to correct the full-scale unit from the above test method. Therefore,

$$A = \frac{t_x}{C_o H_o} \times 1.33 \qquad \text{(Eq. 4.9-9)}$$

$$= \frac{0.0493 \text{ day}}{0.002172 \text{ ton/ft}^3 \times 1.45 \text{ ft}} \times 1.33$$

$$= 20.82 \text{ ft}^2\text{/ton per day of dry solids.}$$

(B) Method II - When representative sludge is not available, the empirical method of determining the area of a thickener is based on either the solids loading or the hydraulic surface loading, whichever yields a greater size.[13] Experience indicates, however, that solids loading generally governs the design.[14] Surface loading rates can be obtained from the operating experience of similar processes. These values, however, vary widely, depending on the degree of sulfite oxidation and the use of flocculants and other process design variables.

Recently, EIMCO conducted a series of sludge settling tests using samples from operating plants. Thickener unit areas were calculated with the results of these tests as outlined in Method I. The areas, without polymer, ranged from 12 to 30 ft^2/ton per day for 25 to 35 wt. percent solids in the underflow for one plant, and from 8 to 12 ft^2/ton per day for 35 to 45 wt. % solids for another plant. When polymers were used, the areas were reduced to 3.5 to 11 ft^2/ton per day and 1.7 to 4.5 ft^2/ton per day, respectively.

Temperature also has an effect on thickener sizing. One study showed that an increase in temperature from 60° to 110°F resulted in a twofold reduction in thickener unit area requirements.

Thickener vendors usually have their own values for the surface loadings from their design experience with similar operations. The trend seems to be to design a thickener without polymer and then to adjust the operation (as discussed in a later section of this report).

Depth--After determination of the area of the thickener, the vendor calculates the side water depth from design experience and the size requirements of the feedwell and the rake arm mechanisms. The residence time for liquor in the thickener, which is the main factor affecting overflow clarity, is calculated from the side water depth and thickener area. The side water depth is often adjusted to give the desired residence time,[15] the most common depths for thickener tanks of 50- to 100-ft diameter being from 8 to 14 ft.

4.9.4 Materials of Construction

In lime scrubbing facilities the thickener is usually a lined or painted mild steel tank with a steel or concrete bottom.

The feedwell and launder are also made of mild steel. The gear mechanisms are of heat-treated steel and alloys such as bronze or alloy steel. To facilitate lubrication, all gear components are normally enclosed in a dust-tight, cast iron housing.

Since the pH of the solution in the thickener tank varies and chloride content may be high, most parts submerged below the solution level are protected from corrosion (including chloride stress corrosion) by an epoxy or rubber coating. The rubber covering operation, however, limits the size of a thickener to a maximum of about 130-ft diameter due to the size limitation of commercial vulcanizers.

Some thickener vendors use special materials for certain parts, because they show better resistance than stainless steel to corrosion by chloride ions. For capital cost savings on tank wall construction, mild steel with corrosion allowance is an alternative material. The general section on corrosion (4.12) provides further information.

4.9.5 Operating Procedure

The design of a thickener largely depends on experience and empirical data, which are not always available. As a result, the thickener is often incorrectly sized.

The retention time of an undersized thickener is shorter than the time required by solid particles to settle down for a normal feed rate. Insufficient settling will result in a high-solids content in the overflow and low underflow densities. If this happens, a proper dosage of polymer can increase the settling rate.

On the other hand, if the thickener is oversized, or if low-solids loading is practiced because of plant load changes, retention time increases. The settled solids may become compacted and cause excessive torque. The proper action in this case is to stimulate a higher feed rate by recycling part of the underflow back to the thickener feedwell.

Another important aspect of the thickener operation is the shutdown process. It is not normally advisable to shut down the thickener for extended periods with appreciable amounts of solids still in the tank. If the bulk of solids inventory in the thickener is not removed before extended shutdowns, settled solids may bed-in around the rakes, causing high torque and extreme difficulty in restarting. Thickener underflow, therefore, should be pumped until it becomes thin. If the thickener has a lifting device, the mechanism should be raised and, if possible, rotated during the shutdown period. If it is not possible to pump out settled solids before shutdown, an alternative procedure is to recirculate underflow back to the thickener feedwell while the rakes are rotating in the lower position. It may also be possible to reduce this recirculation rate below that employed for pumping the thickener underflow during operation. The amount recirculated need only be sufficient to prevent severe compression of the solids, which in turn might cause excessive torque.

After an extended shutdown during which the rakes have been raised, they should be lowered gradually to avoid excessive torque loads. If appreciable solids have bedded-in under the raised rakes, the mechanism should be lowered slowly enough to avoid exceeding the recommended maximum operating torque. In this manner the blades will slice into the bed as the rakes are lowered, fluidizing the mass so that it will flow and be discharged. The time necessary for lowering the rakes could range from a few minutes to several hours, depending on the solids level.

4.9.6 Existing Facilities

The use of the thickener in lime-scrubbing FGD systems is popular; eight of nine plants surveyed in the United States use thickeners. Design and operating data on these facilities are presented in Table 4.9-4.

Performances are satisfactory and no major problems have been reported. Minor problems include underflow plugging, the result of such things as hard hats or welding rods being dropped into the thickener.

Table 4.9-4. EXISTING THICKENER FACILITIES FOR LIME SCRUBBING FGD SYSTEM

Name and Location	Thickener Dimension, ft	Material of Construction	Flocculant	Operating Conditions
Paddy's Run No. 6, Rubbertown Kentucky, LG&E	50 D x 13 H Dorr-Oliver	Mild steel Tank	Betz 1100 (anionic) 5-7 ppm	10% in 19-25% out pH = 7.8-9, 130°F
Cane Run Louisville, Ky. LG&E	85 D x 14 H EIMCO Type B Swinglift	3/16-in. Natural rubber-covered carbon steel tank 316 SS fittings	Betz 1100 (anionic) 5-7 ppm	10% in 17% out pH 7.8-9 130°F
Conesville No. 5 Conesville, Ohio Columbus & Southern Elec.	145 D x 16 H Dorr-Oliver Cable Torq	Rubber-covered carbon steel wall concrete bottom	Nalco 676 (anionic)	15% (max) in 30-40% out pH = 6-7 125°F
Phillips Power Sta., Cresant Township, Pa., Duquesne Light Co.	2 units 75 D x 14 H Dorr-Oliver Cable Torq	Rubber-covered Monel cables	Betz 1120 (anionic) 1-2 ppm	5-10% in 35-40% out pH = 6-8 110°F
Elrama Duquesne Light Co.	2 units 120 D x 8.5 H (side) Dorr-Oliver Cable Torq.	Rubber-covered Monel cables	Floc.-type unknown	5-15% in 35-40% out pH = 6-7 160°F (max)
Bruce Mansfield No. 1 Shippingport, Pa. Penn. Power Co.	1 unit 200 D x 13.5 H Koppers Co.	Rubber-covered carbon steel tank	None	10% in 30% out pH = 8-9 100°F
Mohave Southern Cal. Edison	60 D x 12 H EIMCO Truss-type		Nalco	7% in pH = 7 130°F
Four Corners - 5A Arizona Public Service	100 D EIMCO		None	1% in pH = 7-9

All the thickeners operate with flocculants, except at the Bruce Mansfield plant. This facility has a Koppers Co. thickener, 200 ft in diameter and 12 ft high. It is equipped with a Pennwalt polyelectrolyte feed system. The underflow achieves 25 to 30 percent solids concentration without flocculants. Truss-type arms are supported by a center column with an automatic lifting device. A single pipe in a tunnel is arranged for underflow discharge and a 120-psig water line provides back flushing when needed. Improper lubrication caused high torque in cold weather. This has been corrected. A flocculant testing program is currently in progress.

Paddy's Run No. 6 unit is operating a Dorr-Oliver thickener, 50 ft in diameter and 13 ft high, at 100° to 130°F with a retention time of 4.3 hours. This unit has bridge-mounted, truss-type rake arms with a hydraulic lifting device. Plow blades are mounted on Thixo posts, and the underflow has a multiple piping arrangement with a 40-psig back flushing water connection. This thickener was originally too small to handle untreated slurry at full load, since the slurry contained a higher ratio of calcium sulfite to calcium sulfate than expected. The use of Betz 1100 Polyfloc improved the settling rate sufficiently and a larger thickener was unnecessary. Flocculant is injected into the thickener at a rate sufficient to maintain a concentration of 5 to 7 ppm. Lime is also added to the thickener tank to stabilize the sludge and is consumed at a rate of about 100 lb/ton of dry sludge generated. The feed rate is 200 gal/min at full load. The overflow is 120 to 170 gal/min with less than 0.25 percent suspended solids.

The EIMCO Type B, Swinglift thickener (Figure 4.9-14) at Cane Run is 85 ft in diameter, 14 ft high, and produces 176 gal/min of underflow at 17 percent solids concentration from a feed of 300 gal/min (at full load) of 10 percent solids. The pH ranges from 7.8 to 9 and all the submerged parts are rubber covered. A 0.5 percent solution of Betz 1100 Polyfloc is prepared in a feeding system (described in Section 4.9.3.2) and added to the thickener to make a concentration of 5 to 7 ppm. The underflow has multiple discharge piping in a tunnel with two pumps and a 60- to 65-psig back-flushing water connection. The overflow rate is 250 to 260 gal/min, with less than 0.25 percent suspended solids.

Phillips Power Station installed two units of "Cable Torq" thickeners (Dorr-Oliver), 75 ft in diameter and operating at a pH of 6 to 8. The feed rate is 800 to 1300 gal/min with 4 to 10 percent solids. The underflow solids concentration is 35 to 40 percent. The slurry is flocculated with 1 to 2 ppm of Betz 1120 to aid settling. The underflow has multiple discharge piping in a tunnel with a 90-psig backflush water connection. The overflow has less than 1 percent suspended solids. This station is

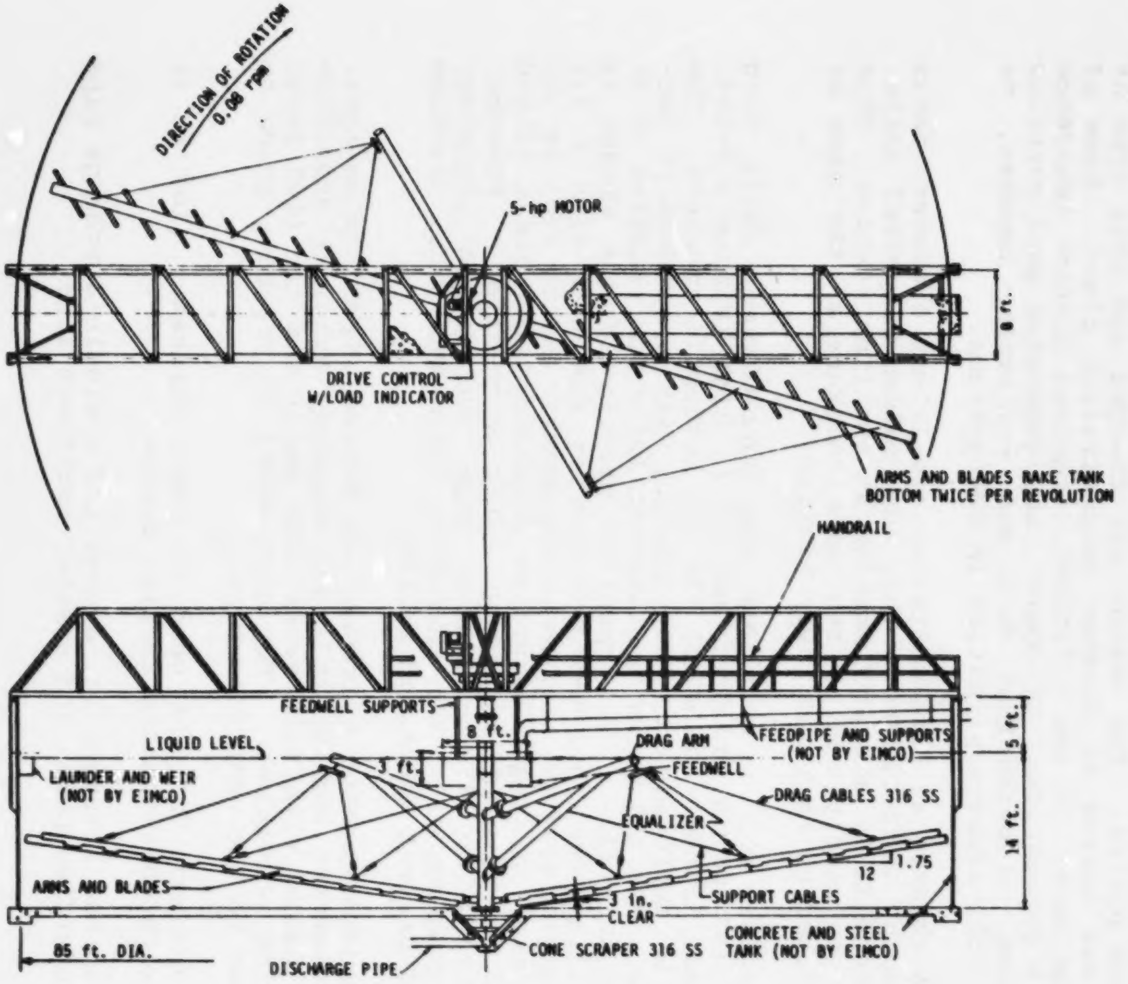

DIRECTION OF ROTATION
0.08 rpm
5-hp MOTOR
8 ft.
DRIVE CONTROL W/LOAD INDICATOR
ARMS AND BLADES RAKE TANK BOTTOM TWICE PER REVOLUTION
HANDRAIL
FEEDWELL SUPPORTS
8 ft.
LIQUID LEVEL
3 ft.
LAUNDER AND WEIR (NOT BY EIMCO)
DRAG ARM
FEEDWELL
FEEDPIPE AND SUPPORTS (NOT BY EIMCO)
5 ft.
DRAG CABLES 316 SS
EQUALIZER
14 ft.
1.75
12
ARMS AND BLADES
3 in. CLEAR
SUPPORT CABLES
85 ft. DIA.
CONE SCRAPER 316 SS
CONCRETE AND STEEL TANK (NOT BY EIMCO)
DISCHARGE PIPE

Figure 4.9-14. EIMCO swinglift thickener at Cane Run Power Station.

currently adding one more thickener by Denver Equipment Co. This 75-ft-diameter thickener is a bridge-supported unit with an automatic lifting device. The truss-type rake arms have blades mounted on Thixo posts. This station tested the Lamella plate-type thickener. The test showed a good overflow quality, but there were some problems with sludge deposits near the bottom of the inclined plates. The design was changed and this type of thickener was tested at Shawnee demonstration plant. Some of the findings were: it was efficient, required shorter residence time than a conventional thickener, and generated good overflow clarification. Insufficient data are available, however, to evaluate a full-scale application in FGD systems.

The thickeners at Elrama Station are 120-ft diameter, Cable Torq models by Dorr-Oliver. They are column-supported units. Operating conditions are the same as at Phillips Station. This station is currently adding two more thickeners, the same as those described at Phillips Power Station.

Conesville No. 5 unit has one Dorr-Oliver, Cable Torq thickener, 145 ft in diameter and 16 ft high (Figure 4.9-15). The walls and launder are steel and the bottom is concrete. The feed rate is approximately 1200 gal/min with a maximum 15 percent solids. The thickener operates at 125°F and produces 25 to 40 percent underflow. The specific gravity of the sludge is 1.2. A 0.3 percent polymer solution is prepared with a BIF polymer feeding system. Polymer consumption (Nalco 676) is 100 to 175 lb/day. A single underflow discharge line has a tilted design and a 70-psig backflush water connection. However, solids settled in the discharge pipe and caused plugging. Underflow pumping rate was therefore increased. The overflow has about 1 percent suspended solids.

The bridge-mounted thickener at Mohave (EIMCO truss-type, 60 ft in diameter and 12 ft high) employed multiple underflow discharge piping with both water (200 psig) and air (100 psig) back-flushing provisions. The unit stood 10 ft above grade to allow access to the underflow piping.

Four Corners Unit 5A used an EIMCO thickener (100 ft in diameter) with an automatic lifting device.

It also had a tunnel for access and a single discharge pipe with two underflow pumps and a water backflush line.

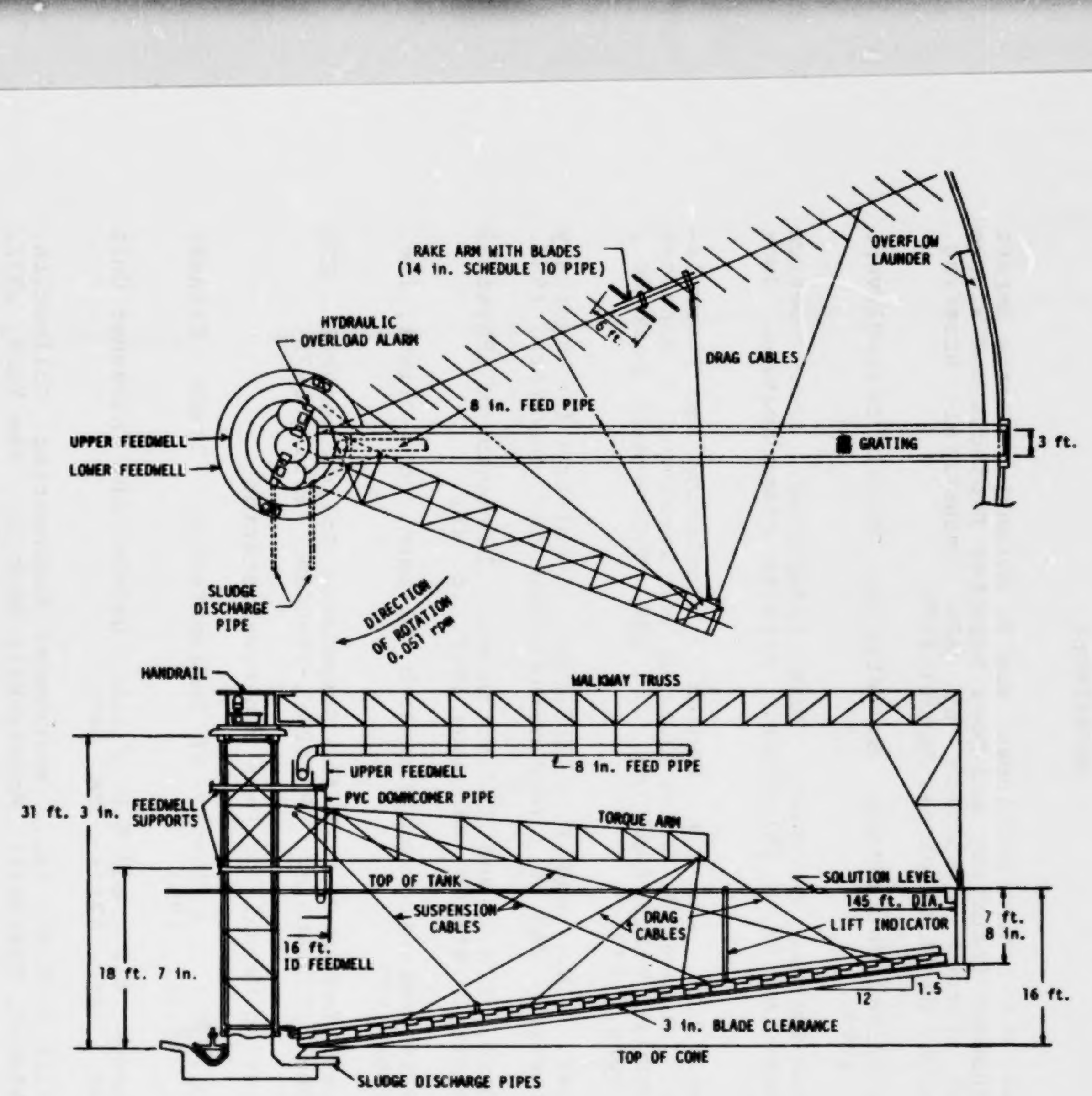

RAKE ARM WITH BLADES
(14 in. SCHEDULE 10 PIPE)
OVERFLOW LAUNDER
HYDRAULIC OVERLOAD ALARM
6 ft.
DRAG CABLES
8 in. FEED PIPE
UPPER FEEDWELL
LOWER FEEDWELL
GRATING
3 ft.
SLUDGE DISCHARGE PIPE
DIRECTION OF ROTATION 0.051 rpm
HANDRAIL
WALKWAY TRUSS
UPPER FEEDWELL
8 in. FEED PIPE
PVC DOWNCOMER PIPE
31 ft. 3 in.
FEEDWELL SUPPORTS
TORQUE ARM
TOP OF TANK
SOLUTION LEVEL
145 ft. DIA.
SUSPENSION CABLES
DRAG CABLES
LIFT INDICATOR
7 ft. 8 in.
16 ft. ID FEEDWELL
18 ft. 7 in.
12
1.5
16 ft.
3 in. BLADE CLEARANCE
TOP OF CONE
SLUDGE DISCHARGE PIPES

Figure 4.9-15. Dorr-Oliver cable torq thickener at Conesville Power Station.

REFERENCES

1. Crowe, J.L., G.A. Hollinden, and T. Morasky. Status Report of Shawnee Cocurrent and Dowa Scrubber Projects and Widows Creek Forced Oxidation at EPA Industrial Briefing. Raleigh, North Carolina, August 1978.

2. Dorr-Oliver Thickeners. Bulletin No. THIC-1, Dorr-Oliver, Inc. 1969.

3. Enviro-Systems Division, Zurn Industries, Inc. Design Information of a Thickener. Private communication, June 1977.

4. Cohen, J.M., and S.A. Hannah. Coagulation and Flocculation. Chapter 3, Water Quality and Treatment, A Handbook of Public Water Supplied, 3rd Ed. McGraw-Hill Book Co., New York. 1971.

5. Sawyer, C.N., and P.L. McCarty. Chemistry for Sanitary Engineers. 2nd Ed., McGraw-Hill Book Co., New York, 1967.

6. Goddard, F.W., and E.J.F. James. Elements of Physical Chemistry. 4th ed. Longmans 1967. p. 462.

7. Private communication with H. H. Oltmann, Dorr-Oliver, Inc. October 1977.

8. Process Design Manual for Suspension Solids Removal. EPA Technology Transfer, EPA 625/1-75-003a, January 1975.

9. Operating Manual for Cane Run Power Station.

10. Kynch, F.J. A Theory of Sedimentation. Trans. Faraday Soc., 48:161, 1952.

11. Talmadge, W.P., and E.B. Fitch. Determining Thickener Unit Areas. I&EC, 47(1): 38, 1955.

12. Metcalf & Eddy, Inc. Wastewater Engineering, Collection, Treatment, Disposal. McGraw-Hill Book Co., New York, 1972.

13. Process Design Manual for Upgrading Existing Wastewater Treatment Plants. EPA Technology Transfer, EPA 625/1-71-004a, October 1974.

14. Schroepfer, G.J., and N.R. Ziemke. Factors Affecting Thickening in Liquid Solids Separation. National Institute of Health, Sanitary Engineering Report No. 156s, March 1964.

15. Private communication with J. Wilhelm. EIMCO Process Machinery Division of Envirotech, October 1977.

BIBLIOGRAPHY

Cornell, C.F. Liquid-Solids Separation in Air Pollution Removal Systems. ASCE Annual and National Environmental Engineering Convention, Kansas City, Missouri, October 21-25, 1974.

CONTENTS

4.10 MECHANICAL DEWATERING EQUIPMENT

Page

4.10.1 Introduction 4.10-1

4.10.2 Centrifuge 4.10-1

- 4.10.2.1 Introduction 4.10-1
- 4.10.2.2 Service Description 4.10-1
- 4.10.2.3 Design Criteria 4.10-3
- 4.10.2.4 Available Equipment and Operating Techniques 4.10-5
- 4.10.2.5 Existing Facilities 4.10-7

4.10.3 Continuous Vacuum Filters 4.10-7

- 4.10.3.1 Introduction 4.10-7
- 4.10.3.2 Service Description 4.10-8
- 4.10.3.3 Design Parameters 4.10-12
- 4.10.3.4 Available Equipment 4.10-23
- 4.10.3.5 Existing Facilities 4.10-23

References 4.10-28

4.10 MECHANICAL DEWATERING EQUIPMENT

4.10.1 Introduction

When underflow from thickeners requires further solids-liquid separation, continuous mechanical dewatering devices such as centrifuges or continuous vacuum filters can be used. These methods are used to remove sufficient water from liquid sludges so that the sludge can be easily handled. Ideally, a dewatering operation is designed to capture all the solids from a thickened slurry at the lowest cost. The dewatering process produces a solid cake having optimal physical handling characteristics and moisture content for subsequent processing. Process reliability, ease of operation, and compatibility with the plant environment also need to be optimized.

This section will acquaint the reader with the various types of mechanical dewatering equipment that are currently used or that have great potential for future application in lime scrubbing FGD systems, and also with the parameters considered to be important in the design and operation of the equipment.

4.10.2 Centrifuge

4.10.2.1 Introduction--

Centrifuges are widely used for separating solids from liquids. They effectively create high centrifugal forces (about 4000 times the force of gravity). The equipment is normally small and can separate bulk solids rapidly with short residence time. The specially developed centrifuges are reliable and efficient machines. Their products are consistent, uniform, and easily handled; however, they are not effective in producing clarified overflow and, because of high rates of wear, erosion and corrosion require special materials of construction and frequent maintenance.

4.10.2.2 Service Description--

Centrifugal separators are divided into two broad classes: those that settle and those that filter. In the first class, centrifugal force is utilized to increase the settling rate over that obtainable by gravity settling; this is done by increasing the apparent difference between densities of the phases. In a filtering centrifuge, the pressure needed to force the liquid through a septum is generated by centrifugal action. The main interest in this section is the continuous settling centrifuge for separating a slurry into a clear liquid and a very thick sludge.

Figure 4.10-1 shows a continuous bowl centrifuge for solids settling. The two principal elements of this centrifuge are the rotating bowl (which is the settling vessel) and the rotating screw conveyor (which discharges the settled solids). The bowl

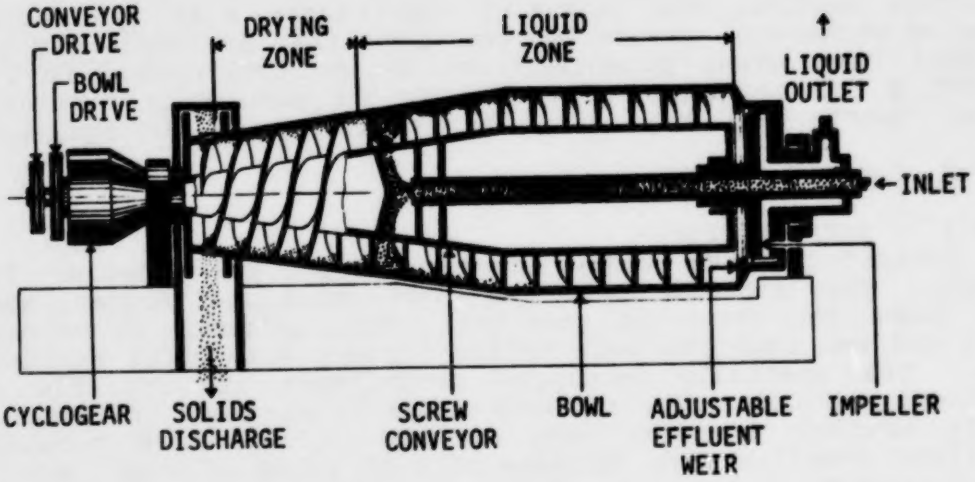

CONVEYOR DRIVE
BOWL DRIVE
DRYING ZONE
LIQUID ZONE
LIQUID OUTLET
INLET
CYCLOGEAR
SOLIDS DISCHARGE
SCREW CONVEYOR
BOWL
ADJUSTABLE EFFLUENT WEIR
IMPELLER

Figure 4.10-1. Solid bowl centrifuge.

Source: Pfandler Co.

has adjustable overflow weirs at its larger end for discharge of clarified effluent and solids discharge ports on the opposite end for discharge of dewatered sludge cakes. As the bowl rotates, centrifugal force causes the slurry to form an annular pool, the depth of which is determined by the adjustment of the effluent weirs. A portion of the bowl is of reduced diameter to prevent its being submerged in the pool; it thus forms a dewatering zone for the solids as they are conveyed across it. Feed enters through a stationary supply pipe and passes through the revolving conveyor hub into the bowl itself. As the solids settle out in the bowl, they are picked up by the conveyor screw and transported to the solids discharge ports. A recent study[1] indicated that, depending on feed rate and bowl rotation speed (3300 to 5400 rpm), solids concentration ranged from 0.7 to 4 weight percent in the effluent and from 60 to 70 weight percent in the cake when the feed was 16 to 20 weight percent.

4.10.2.3 Design Criteria--

It is extremely important to note that there are two operating zones in the horizontal bowl conveyor centrifuge: the liquid zone and the drying zone. Early theoretical consideration of centrifugal dewatering mechanisms focused primarily on the relationship between the centrifuge and a hypothetical sedimentation basin as they are affected by the employment of very high gravity forces. The sigma formula is normally used to describe the operation of a continuous, horizontal, helix-type centrifuge. This formula shows that the centrifuge capacity factor (which is proportional to the rate of liquid clarification) varies with the surface area of the liquid and the centrifugal force.[2]

$$\Sigma = \frac{\pi b \omega^2}{2g} (3r_2{}^2 + r_1{}^2)$$

where Σ = Sigma centrifuge capacity factor, ft^2

b = Length of cylindrical bowl, ft

ω = Rate of rotation, rad/s

r_2 = Radius of inner bowl wall, ft

r_1 = Radius of retained liquid surface, ft

g = Gravitational constant, ft/s per second

Sigma and other theoretical relationships based on easily measured machine dimensions are useful tools when employed by the centrifuge designer for estimating scale-up relationships in geometrically similar machines. Unfortunately, the widespread use of the sigma formula has led to some centrifuge specifications based only on sigma.[3]

The capacity of a helical centrifuge is usually somewhat lower than that predicted by theory. The action of the conveyor tends to resuspend solids particles in the liquid. In addition, at low feed rates, complex fluid dynamic effects have to be taken into account.[2]

The important machine variables that affect centrifuge performance are as follows:

- Bowl design
  - Length/diameter ratio
  - Bowl angle
  - Flow pattern
- Bowl speed
- Pool volume and depth
- Conveyor design
- Relative conveyor speed
- Sludge feed rate

Settling time and surface area can be increased for a given diameter bowl by increasing the length/diameter ratio. Although the detention time is increased by an increase in bowl diameter, lower centrifugal forces result because of mechanical limitations. Length/diameter ratios of 2.5 to 3.5 are customarily employed. The designer can effectively increase the length of the liquid zone of the bowl by making the discharge angle of the screw conveyor steeper. Centrifugal forces can also be increased by increasing the rotation speed.

In any centrifuge application, the centrifuge manufacturer will determine the length/diameter ratio and the bowl angle; however, wide variations in performance can be made by changing other variables.

The primary operating variables are bowl speed and pool volume. While increasing the bowl speed increases the centrifugal forces and favors increased clarification, it also makes the settled solids become more difficult to discharge. Excessive bowl speed tends to lock the bowl and conveyor together and increases abrasion.

Pool depth affects both clarification and cake dryness. Lowering the pool depth extends the drying zone, increases the dewatering time, and produces a drier cake. Within limits, increasing pool depth increases clarification by increasing detention time. Just as in plain sedimentation, however, too great a depth prevents a particle from reaching the sediment zone prior to its being discharged in the effluent. At too shallow a depth, the moving conveyor tends to redisperse settled solids.

Conveyor speeds are normally designed or adjusted to a minimum turbulence inside the pool while still providing sufficient conveying capacity. Low speeds also reduce the rate of wear on the conveyor blades.

The sludge feed rate is clearly one of the more important variables. It affects both clarity and sludge cake dryness. The handling of a larger volume of sludge per unit of time in a given bowl means less retention time and a decrease in solids recovery. It also usually results in drier solids in the cake because of the higher loss of fines with the centrate. Fines have a tendency to retain more water.

Successful application of continuous bowl conveyor centrifuges for removal of solids requires consideration of numerous factors; proper scale-up is the major one. To obtain predictable results, values must be available for the following variables:

- Wet cake discharge rate
- Solids dewatering time under centrifugal force
- Conveying torque for cake solids
- Liquid clarifying ability
- Resistance to abrasion from slurry solids
- Stability of centrifuge feed
- Physical nature of solids being handled.

The scale-up factors have provided accurate predictions of full-scale performance.[4]

4.10.2.4 Available Equipment and Operating Techniques--

Bowl centrifuge--There are two types of bowl centrifuges for solids removal, countercurrent and concurrent. The countercurrent centrifuge assembly consists of a rotating unit comprising a bowl and conveyor joined through a planetary gear system designed to rotate the bowl and the conveyor at slightly different speeds in the same direction. The bowl, or shell, is supported between two sets of bearings and includes a conical section at one end. This section forms the drying zone (on the dewatering beach) over which the helical conveyor screw pushes the sludge solids to outlet ports and then to a sludge cake discharge hopper. The opposite end of the bowl is fitted with an adjustable outlet weir plate to regulate the level of the sludge pool in the bowl. This plate also discharges the centrate through outlet ports, either by gravity or by a centrate pump attached to the shaft at one end of the bowl. Sludge slurry enters the rotating bowl through a stationary feed pipe extending into the hollow shaft of the rotating bowl. The sludge feed enters a baffled, abrasion-protected chamber for acceleration before it is discharged through the feed ports of the rotating conveyor hub into the sludge pool in the rotating bowl. The sludge pool takes the form of a concentric annular ring of liquid sludge on the inner wall of the bowl. Separate motor sheaves or a variable-speed drive can be used for adjusting the bowl speed for optimum performance.

Usually, all parts of centrifuges that contact liquids are made of ductile, generally corrosion-resistant, grade 316 stainless steel. The ductility of the stainless steel prevents catastrophic brittle failure. Hard facing materials (such as tungsten carbide) are applied to the leading edges and tips of the conveyor blades, the discharge ports, and other wearing surfaces, because of the abrasive nature of the lime-generated sludges. Such wearing surfaces may be replaced, when required, by welding.

In a cocurrent centrifuge, incoming sludge is carried by the feed pipe to the end of the bowl opposite the solid discharge. As a result, settled solids are not disturbed by incoming feed. Solids and liquids pass through the bowl in a smooth parallel-flow pattern. Turbulence is substantially reduced. Solids are conveyed over the entire length of the bowl before discharge to provide better compaction and a drier cake and to reduce flocculant demands.

Addition of conditioners--Conditioners may be added to the centrifuge feed to increase settling rates. Both inorganics and polymers agglomerate fine particles by neutralizing surface charges, thereby accelerating, settling, and clarifying thickener overflow. Polymers possess less neutralizing power than inorganics, but they have a higher capacity for "bridging" (simultaneous attachment) to two or more solid particles than do inorganic coagulants. They also provide the advantage of a very large increase in the size of the floc, which greatly increases their settling rate. (See Section 4.9.3.2.)

Lower-speed centrifuges--These centrifuges have been developed primarily in Europe to achieve high solids capture and minimize the recirculation of solids without the use of high polymer dosages. The sludge is introduced into the centrifuge with the lowest possible acceleration and turbulence. The machine is operated at about 1500 rpm, depending on the diameter of the centrifuge. This low rpm gives a low noise level and a minimum of wear and tear on the rotating parts. Low conveyor differential speeds are also used. Among the reported advantages of these machines are lower capital costs, lower power requirements, lower noise level, and reduced maintenance when compared with higher-speed centrifuges. The use of large pool volumes, reduced internal turbulence, and low centrifugal forces (500 to 800 g) combine to reduce shearing forces on the floc and to improve conveying characteristics.

4.10.2.5 Existing Facilities--

Bird 18-in. x 28-in. continuous bowl centrifuges are used to dewater scrubber waste sludge and to recover dissolved scrubbing additives at the test facility of the Tennessee Valley Authority (TVA) coal-fired Shawnee Power Station near Paducah, Kentucky. Normal operating conditions usually consist of a feed stream flow of 15 gal/min at 30 to 40 weight percent solids, a centrate of 0.1 to 3.0 weight percent solids, and a cake of 55 to 65 weight percent solids. Approximately 30 percent of the solids are fly ash; the remaining solids are predominantly calcium sulfate and sulfite. The centrifuge operates at 2050 rpm.

The material of construction is 316L stainless steel with Stellite hard facing on the feed ports, conveyor tips, and discharge parts. The centrifuge was inspected in June 1978 after 6460 hours of operation since the previous factory servicing. The machine was judged to be generally in fair condition, but some components were badly worn and in need of factory repair. Serious wear was observed at the conveyor tips on the discharge end and at the junction of the cylinder and the 10-deg section of conveyor. Wear was also present at the casing head plows and solids discharge head near the discharge ports. The bowl and effluent head were in good condition.[5]

Recently, EIMCO (Division of Environtech Corp.) conducted a test program for EPRI at Bruce Mansfield, Phillips, and Conesville stations to determine design parameters and evaluate the economics of centrifuges. Sharpless Models P-600 and P-660 Super-D-Canter (Pennwalt Co.) were used for these tests. The results indicated that over 90 percent solids could be recovered with a bowl speed of 4000 rpm or higher. The discharged cake solids ranged from 60 to 70 weight percent and were highly fluidic and thixotropic.[1]

4.10.3 Continuous Vacuum Filters

4.10.3.1 Introduction--

Vacuum filters are normally the most economical mechanical dewatering devices for continuous service. They are widely used because they can be operated successfully at relatively high turndown ratios over a broad range of solids concentrations in the feed. A vacuum filter provides more operating flexibility than any other type of dewatering device.

Five types of vacuum filters are applicable to lime-generated sludge systems: drum, belt, disk, horizontal belt, and pan. Each has different characteristics and applicability.

Since the rotary-drum vacuum filter is widely used for continuous service and is currently used in most scrubber systems, this section will concentrate on it. A detailed discussion of other filter types will be presented under "Available Equipment" in Section 4.10.3.4.

Since the vacuum filter will not provide an acceptable filter cake if the solids content of the feed is too low, an upstream thickener, centrifuge, or hydroclone is normally required.

4.10.3.2 Service Description--

A rotary-drum vacuum filter (Figure 4.10-2) is widely used for continuous service. The drum is divided into sections, each connected through ports in the trunnion to the discharge head. The slurry is fed to a tank (or vat) in which the solids are held uniformly in suspension by an agitator. As the drum rotates, the faces of the sections pass successively through the slurry. The vacuum is applied in turn to each section (pickup or form zone in Figure 4.10-3) and the filtrate is drawn through the filter medium, depositing the suspended solids on the filter drum as cake. As the cake leaves the slurry, it becomes completely saturated with filtrate and undergoes dewatering by the simultaneous flow of air and filtrate (cake drying zone). The drying is negligible when air is used at room temperature. Finally, the cake is removed in the discharge zone by a scraper, which may be assisted by a slight air reversal through the filter valve.

Continuous rotary-drum vacuum filters of this general type provide high filtering rates and are available in a wide range of sizes, from about 3 to 800 ft^2 of filter area.

A typical filter system is presented in Figure 4.10-4. The lower pipe connection at the filter valve accommodates the liquid pulled through the sections in the pickup zone. The upper filter valve connection carries the liquid and air pulled through the cake in the dry zone. When a drum section reaches the end of its cycle, the vacuum is released and a low-pressure air supply discharges the cake through the filter tank chutes to the conveyor below for final disposal.

Liquid and air enter the side connection of the filtrate receiver, where the liquid drops down to the filtrate pump and the air is pulled through the top connection of the receiver to the moisture trap. Each receiver may be equipped with a vacuum-limiting device to admit air if the design vacuum is exceeded, a condition that would cause the pump to overload. The receiver also acts as a reservoir for the filtrate pump suction. The receiver is usually designed to give a maximum air velocity of 2.5 to 5 ft/min and a minimum air detention time of 2 to 3 min to prevent carryover of the liquid. Check valves on the discharge side of the pumps are usually provided to minimize

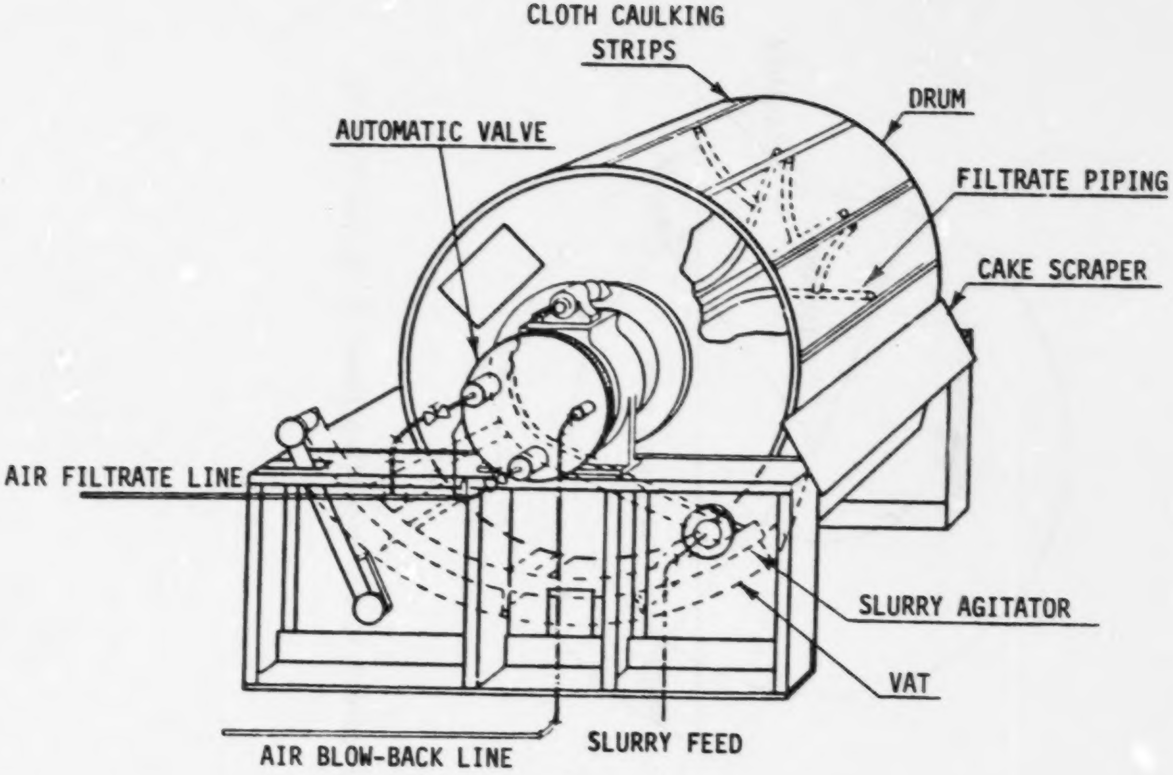

CLOTH CAULKING STRIPS
DRUM
AUTOMATIC VALVE
FILTRATE PIPING
CAKE SCRAPER
AIR FILTRATE LINE
SLURRY AGITATOR
VAT
SLURRY FEED
AIR BLOW-BACK LINE

Figure 4.10-2. Cutaway view of a rotary-drum vacuum filter.[3]

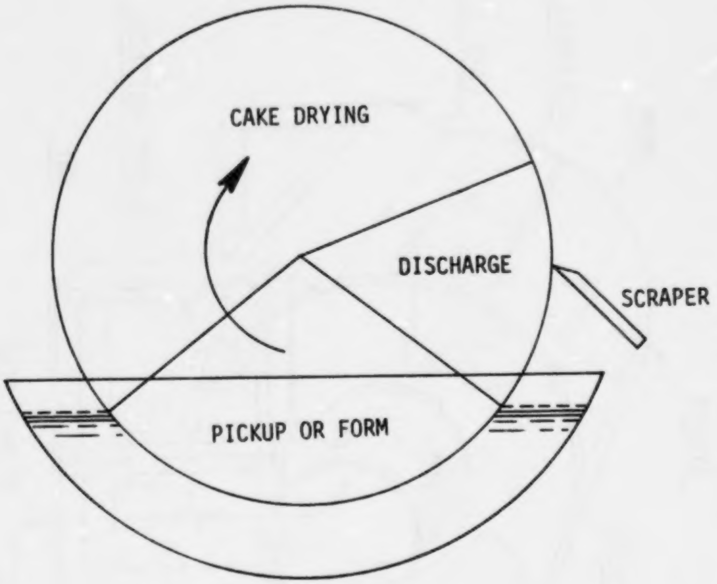

CAKE DRYING
DISCHARGE
SCRAPER
PICKUP OR FORM

Figure 4.10-3. Operating zones of vacuum filters.

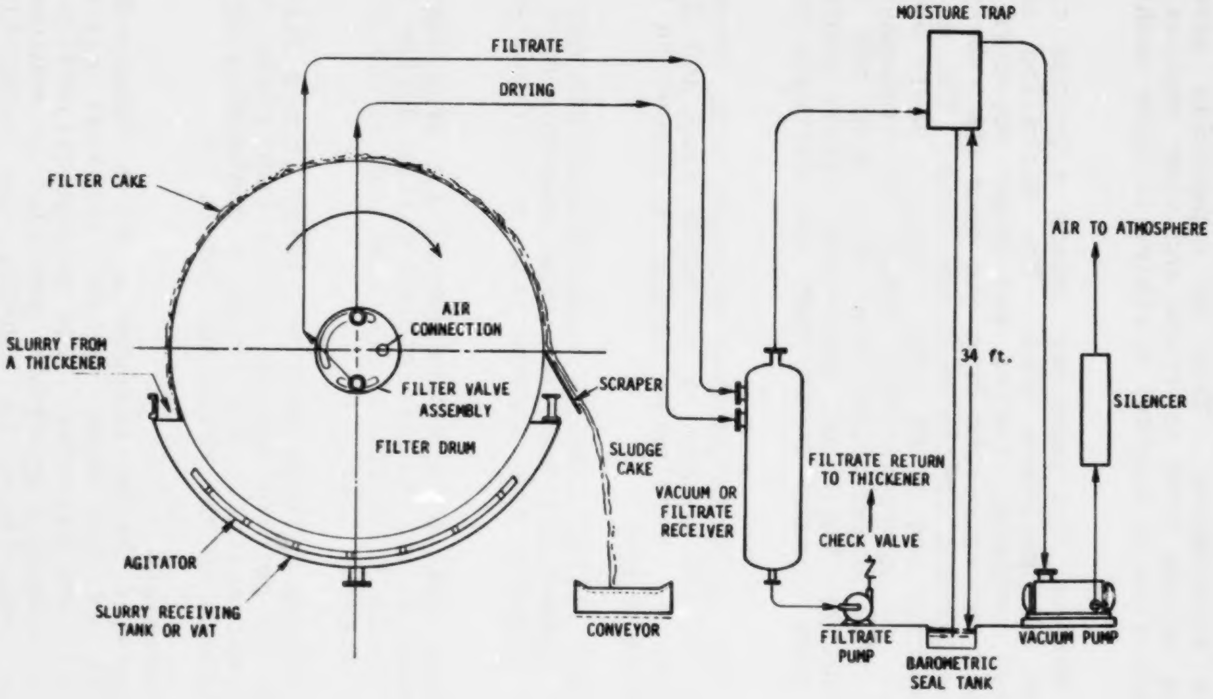

FILTRATE
DRYING
MOISTURE TRAP
FILTER CAKE
AIR TO ATMOSPHERE
AIR CONNECTION
SLURRY FROM A THICKENER
34 ft.
SCRAPER
FILTER VALVE ASSEMBLY
SILENCER
FILTER DRUM
SLUDGE CAKE
FILTRATE RETURN TO THICKENER
VACUUM OR FILTRATE RECEIVER
CHECK VALVE
AGITATOR
SLURRY RECEIVING TANK OR VAT
CONVEYOR
FILTRATE PUMP
VACUUM PUMP
BAROMETRIC SEAL TANK

Figure 4.10-4. Flow sheet for continuous rotary-drum vacuum filtration.

air leakage back to the vacuum pump through the filter pump and receiver.

A two-receiver system is employed in those cases where vacuum regulation is considered. This is especially advantageous when the cake solids tend to crack and when regulation is desired to limit air flow or control cracking in cake washing systems.

The air pulled through the receiver enters a bottom tangential connection at the moisture trap. The spiraling air, upon entering the trap, expands, cools, and drops moisture in the form of water vapor and entrained droplets from the receiver through the bottom connection of the moisture trap. The moisture trap has a barometric leg 34 ft long. Since a 34-ft water differential pressure is approximately equal to atmospheric pressure, any water that enters the trap will drop out the barometric leg by gravity. The trap, therefore, offers protection to the vacuum pump in the event that the filtrate pump should fail.

Air pulled out the upper tangential moisture trap connection is carried over to the intake of a vacuum pump and discharged to the atmosphere. A silencer should be placed on the pump discharge to reduce noise.

The lime-generated filter cake is compressible and may be thixotropic, in that subsequent handling (via conveyor belt or trucking, etc.) may liquify the sludge into a difficult-to-handle putty.

A recent filtration test by EIMCO personnel for EPRI showed that the lime-generated filter cakes cracked easily during the early period of dry cycle.[4] A short dry time (about 10 s or less) is desirable to prevent this.

Plants that use vacuum filters dewater slurry from a thickener containing 20 to 35 percent solids into filter cakes containing 45 to 75 percent solids. The filtrate containing up to 1.5 percent solids returns to the thickener for reuse.

4.10.3.3 Design Parameters--

Mechanical design--The major components of a rotary-drum vacuum filter consist of the drum, grids, internal piping, receiving tank (or vat), and agitator. The mechanical design of these components is a standard procedure provided by equipment suppliers. Corrosion resistance is usually the controlling factor in selection of the filter equipment. The sludge pH can vary from 5 to 11. In addition to sulfurous acids, the slurries contain chloride ions, which can be highly corrosive. Many operators report evidence of chloride stress corrosion throughout the entire FGD system. K_{ISCC} should therefore be used as one of the design parameters; the reader is referred to Section 4.12.3 for additional information.

All rotary-drum vacuum filters are available in a variety of materials, including carbon steel, stainless steel, special alloys, rubber-covered steel, plastic-covered steel, or all plastic. Use of special materials requires higher capital costs. Nevertheless, when moving parts or wear surfaces are exposed to corrosive/erosive environments, they should be properly protected with coatings of epoxy-based materials, FRP, rubber, or similar protecting substances. Specific areas of concern are internal piping, wear plates, filter valves, filter cloths, the filter drum and grid, the filtrate pump, and external piping.

(A) Major components - Figure 4.10-5 shows the drum without covers and displays the internal piping, which may be made of thin-wall stainless steel tubing, i.e., Schedule 10, 304 stainless steel. The drum heads are usually of mild steel; the drum face and media are made of 304 stainless steel for long service with minimum maintenance. Large manholes on the drum covers provide easy access to all internal areas.

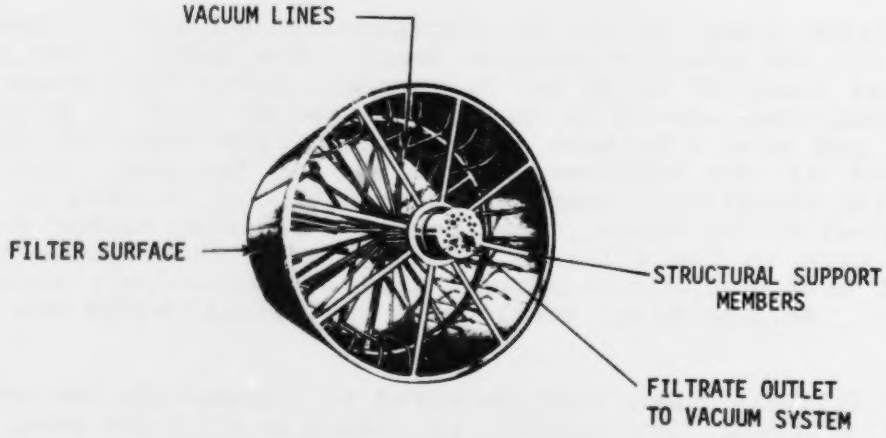


Figure 4.10-5. Drum and internal piping.

Source: Ameteck Process Equipment Division.

The slurry receiving tank and the agitator can be made of carbon steel, rubber-covered for corrosion protection.

Some suppliers offer plastic filter equipment made entirely of high-strength FRP. The corrosion resistance of this equipment is excellent. The available filtering area, however, is limited to about 100 ft^2, and the cost of the equipment is greater than the cost of steel.

Grids that support the filter media are available in wire screen, molded rubber, polypropylene, and other plastics with open areas up to 55 percent. The snap-in grid design greatly simplifies maintenance.

(B) Auxiliary equipment - The important auxiliary equipment items are the vacuum receiver, the filtrate pump, and the vacuum pump. Design considerations for these items will be discussed in the following paragraphs.

To discharge the filtrate requires a pump to overcome the suction head created by vacuum. A check valve is placed on the filtrate pump discharge to ensure that no air is sucked back into the system. Should this occur, the system would be inoperable. Thought must be given to the application of filtrate pump discharge. The filtrate pump is rated for a given total dynamic head (TDH) in gallons per minute and for net positive suction head (NPSH).

Filtrate pumps should be specifically designed to operate at very low net positive suction heads. The design inlet pressure is at least 20 to 22 in. Hg vacuum. Centrifugal pumps are common, but they should be protected against loss of prime in the pump and have a balance or equalizing line connected from a high point of the receiver to the eye of the pump impeller. Nonclogging centrifugal pumps are used with coil filters or with coarse metal filter media. They permit a somewhat higher solids concentration in the filtrate. Self-priming centrifugal pumps are used most frequently because they are relatively maintenance-free. Self-priming, nonclogging centrifugal pumps are also used.

The filtrate pumps must be sized to accommodate the entire range of filtrate flow rates. In sizing a filtrate pump, the designer must recognize that the rate of filtrate flow is a function of the mode of chemical conditioning. Polymers allow the sludge to drain much more rapidly than do inorganic conditioners (see Section 4.10.2.4).

The piping from the filter valve on the filtrate pump discharge must be in a horizontal plane or dropped vertically to the receiver side connection. The moisture trap height above the receiver is inconsequential as long as the bottom connection of the trap is above the top connection of the receiver, and at least a 34-ft tail leg is on the trap. All pieces of equipment should be placed as close as possible to each other, and unnecessary pipe turns and bends should be avoided to reduce friction head loss. Pipe connections and auxiliary equipment sizes should be in accord with the filter manufacturer's recommendations.

Filtrate may also be discharged from the receiver by means of a barometric leg rather than a filtrate pump. This type of system is beneficial from the standpoint that barometric legs require minimal maintenance compared with filtrate pumps. Discharging filtrate by a barometric leg is not always possible, however, because of plant elevation limitations. If a barometric leg discharge is used, it should be immersed in the cleanest circulating water in the plant to prevent its being plugged with solids. It is recommended that an electrode be placed in the line from the receiver to the trap so the electrode, when contacted by water, will automatically shut off the vacuum pump motor

Wet-type vacuum pumps are most popular because they are easily maintained and provide sufficient vacuum. In such a system, the vacuum pump uses water for its sealing medium, and the moisture trap, the barometric leg, and the seal tank shown in Figure 4.10-5 are eliminated. Because wet-type vacuum pumps use seal water, the water must be of good quality; if it is hard and unstable, a sequestering agent may be needed to prevent carbonate buildup on the seals, but no moisture trap protection is required.

Machine variables--A number of variables affect the operation of the filter system:

- Feed solids concentration
- Filter cycle time
- Drum submergence
- Agitation
- Cake air requirements
- Filter media.

The effect of each variable on the performance of the filter system is discussed below:

(A) Feed solids concentration - This variable is of utmost importance in the filtration step, and for this reason a thickening device precedes the filter to ensure a feed solids concentration consistent with economic and efficient operation. A general plot of dry cake output vs. feed solids concentration is shown in Figure 4.10-6.

Each slurry has its own filtration characteristic curve, but generally the slurry exhibits a sharp incremental rate above "a." Controlling the solids concentration between "b" and "c" will therefore require less filtration area, and filter operating costs will be reduced. Above point "c," the slurry becomes relatively viscous and its transportation to the filter is difficult. The curve becomes asymptotic, and further slurry thickening is impractical and uneconomical in view of the slight increment in cake rate.

(B) Filter cycle time - Cycle time of a continuous vacuum filter is the time required for the filter to make one complete revolution and is expressed in terms of minutes per revolution (mpr). During the cycle, three phases of filter operation occur: cake formation or pickup, cake dewatering or drying, and cake discharge by air blowback or release. At the end of a given cycle, the filter has discharged a given weight of cake per given amount of filter area, and a dry cake rate in pounds/hour per square foot of filtering area is obtained. The general appearance of a log-log plot of dry cake rate vs. cycle time for one filter feed solids concentration is shown in Figure 4.10-7. The slope of the curve is negative and is theoretically equal to -0.5.[5] Empirical values are usually equal to the theoretical. Stated in terms of increasing or decreasing filter cake output as a function of changing cycle time, the resulting change in cake rate is equal to the square root of [the original cycle time divided by the new cycle time]. Expressed mathematically, this relationship appears as follows and is based on the assumption that solids concentration and cake compressibility remain constant:

$$\text{New filter cake rate} = \text{old cake rate}\sqrt{\frac{\text{old cycle time}}{\text{new cycle time}}}$$

It can be seen that cycle time is of great importance in the filter operation. For this reason, the filter is equipped with a variable-speed filter drive operating with 6:1 ratio limits, usually of 1.5 to 9 mpr. Consequently, for a given amount of filter area, cake output can be doubled, or possibly tripled or halved, as the situation requires.

Cycle time is an important function of filter cake moisture content and filter cake dischargeability. Where possible, it is strongly recommended that the filter be sized at a cycle time at least 3 mpr, and preferably as 4 mpr. Appreciable decreases in cake moisture occur at cycle times slower than 3 mpr. In addition, thicker cakes resulting from slower cycle times give complete and easy cake discharge. Easy cake discharge means sizable reductions in filter maintenance costs.

(C) Drum submergence - Increasing the drum submergence increases the form cycle time and usually results in an increased yield of thicker but wetter cake. Submergence is usually kept between 15 and 25 percent to provide long drying time and to keep the cake moisture content at a minimum.

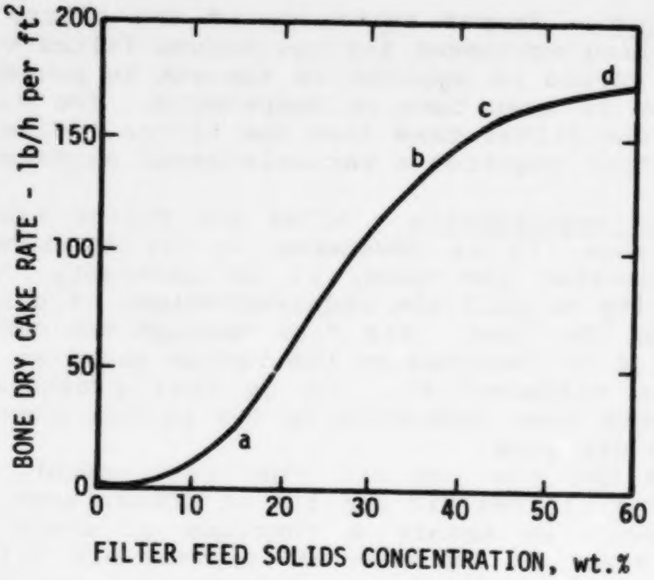


Figure 4.10-6. Filtration rate vs. feed solids.

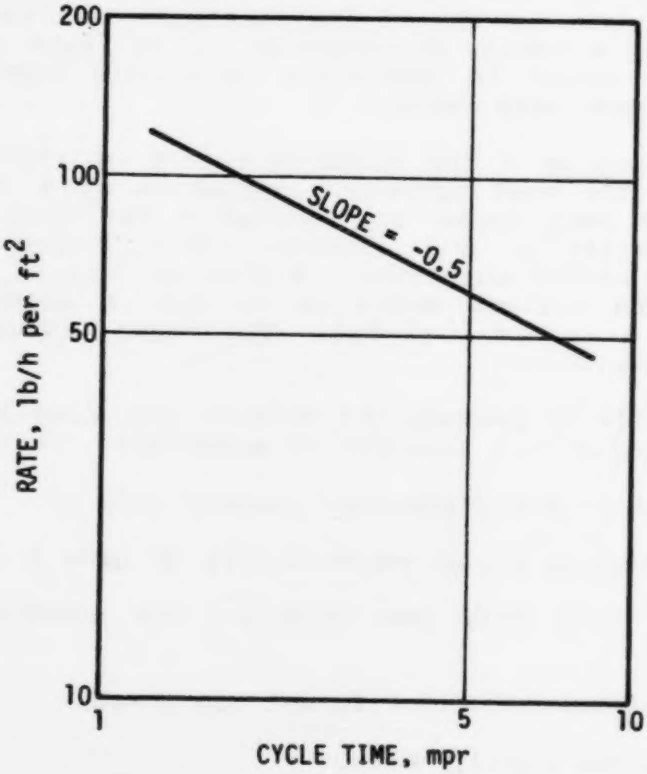


Figure 4.10-7. Dry cake rate vs. cycle time.

(D) Agitation - Proper agitation of the slurry requires variable-speed mixing equipment for the vacuum filter vat. Only enough agitation should be applied in the vat to prevent solids classification and to keep them in suspension. Too much agitation will loosen the filter cake from the filter medium. Therefore, optimum control requires a variable-speed agitator.

(E) Cake air requirements - After the filter cake emerges from the pickup zone, it is dewatered in the dry-zone part of the cycle. To dewater the cake, it is necessary to provide vacuum pump capacity to pull the required volume of air from the atmosphere through the cake. Air flow through the cake creates a resistance, which is recorded on the vacuum gauge as vacuum or negative pressure differential. It is this pressure differential that effects cake formation in the pickup zone and cake dewatering in the dry zone.
Each filter cake has its own air flow requirement, which is approximately 3 ft^3 of free air per ft^2 of filter area. The air flow rate, however, is mainly a function of cycle time and solids particle size; in the case of compressible filter cakes such as the lime-generated cake, an increase of air flow rates would decrease cake moisture content. Unfortunately, lime-generated cake cracks easily during the dry cycle and most of the air passes through the cracks. A short dry time (about 10 s) and 2 to 3 ft^3/min per ft^2 of air therefore seem to be optimum. This permits a vacuum differential of at least 22 in. Hg across the cake, which is desirable to obtain minimum cake moistures and maximum cake rates.

(F) Filter medium - The right selection of filter medium is essential for the most effective operation of a continuous filter. A great many types are available for drum filters. Blinding characteristics and chemical conditioning play an important role in medium selection. Filter leaf tests should be conducted with the various media as an aid in selecting the optimum one for a specific sludge. The ideal medium has the following characteristics:

- It is able to perform the desired liquid/solids separation and give a filtrate of acceptable clarity.
- The filter cake discharges readily from it.
- It is strong enough mechanically to give a long life.
- It is chemically resistant to the materials being handled.
- Its resistance to flow is not too great.
- It does not rapidly blind.

Obviously, some reasonable compromise must be reached between these objectives, since all of them cannot be optimized simultaneously. Years ago, cotton duck was about the only filter medium available to the vacuum filter operator. Today, a wide range of choices exists. Filter media are available to cover any filtration situation, so blinding should not occur and a maximum medium lifetime can be obtained. For a lime scrubbing system, polypropylene appears to be most economical while also providing adequate service and good chemical resistance.[7] Other choices are polyethylene, nylon, and Dacron.

Operational features--Filters are normally installed in buildings with adequate weather protection. Besides the machine variables, the main considerations are proper feeding of the slurry to the filter, the disposition of the discharged cake solids and the separated filtrate, and instrumentation of the operation.

Feeding the filter is extremely important. Improper feed piping to the filter will result in a poor operation because of nonuniform solids concentrations in all parts of the filter tank. Feeding should generally be accomplished at the side feed; this is done in parallel flow with the direction of the drum so that the slurry will have an opportunity to filter upon contact with the cleaned surface of the drum. In addition, the coarse particles will tend to collect first on the drum, thereby providing a "precoat" to aid filtration in the remaining pickup cycle.

Normally, the filters are installed at an elevated location. This allows the cake solids discharging from the filter to drop into a chute to a storage hopper for easy loading into a truck. If an elevated position is undesirable, a belt conveyor may be employed to collect the discharged solids from the filter and carry them up to a raised storage hopper, again to permit easy loading into trucks.

Finally, an electrical interlock system is worthy of mention for the purpose of additional precautions. The simplest and safest interlock in the filter system would be to interlock the filter cake conveyor, filter drive, and vacuum pump such that if the cake conveyor failed, first the filter drive and then the vacuum pump would kick out. This would ensure that a cake buildup would not occur in the filter discharge chute in the event of cake conveyor failure. Moreover, should the filter drive fail, the vacuum pump would stop and slurry in the filter tank would not have a chance to "dewater" itself to the degree that only solids remain.

Sizing criteria--A standard rotary drum vacuum filter can be purchased from many suppliers. Correct sizing, i.e., the determination of the correct filter area, is important for economical operation since size usually accounts for an appreciable portion of the capital and operating costs. Sufficient filter area must be provided for maintenance of the sludge solids removal rate necessary to prevent excessive solids accumulation in the plant.

The size of a filter for a given application is inversely proportional to the slurry feed concentration.[7] Thus, if a thickener is installed upstream, it is important to determine the minimum underflow concentration encountered in average operation of the unit. When the filter is sized at this minimum solids concentration, it will have adequate capability to dewater the solids output of the plant.

The filtration rate for sludges containing almost total calcium sulfite from lime scrubbing appears to range from 50 to 60 lb/h per ft^2. On the other hand, filtration rates of sludges in which calcium sulfate crystals dominate range between 150 and 250 lb/h per ft^2.[7]

Because of the wide variations in slurry characteristics of the lime-based FGD system, it is advisable to run laboratory vacuum filtration tests on representative samples (if available) of the sludges to be dewatered; this allows accurate sizing of the filter equipment.[2,3,8] The two test procedures used for determining the filterability of sludges are the Buchner funnel method[3] and the filter leaf technique. The Buchner funnel method enables a determination of the relative effects of various chemical conditioners and the calculation of the specific resistance of the sludge, but it is seldom used for the calculation of required filter area because it presents many difficulties in providing data. The filter leaf test (Figure 4.10-8) is used to determine the required filter area.[2,3] It employs a test leaf over which is fitted a filtering medium identical to that which will be used on the full-scale filter. The procedure for conducting filter leaf tests is as follows:[3]

1. Condition approximately 2 liters of sludge for filtration. The sludge should be thickened to a minimum concentration of 2 percent or to that anticipated for the full-scale application.

2. Apply desired vacuum to filter leaf and immerse in sample 1-1/2 min (maintain sample mixed). The test leaf normally is inserted upside down in a representative slurry to simulate the cake formation zone of the drum filter. This portion of the cycle is cake formation.

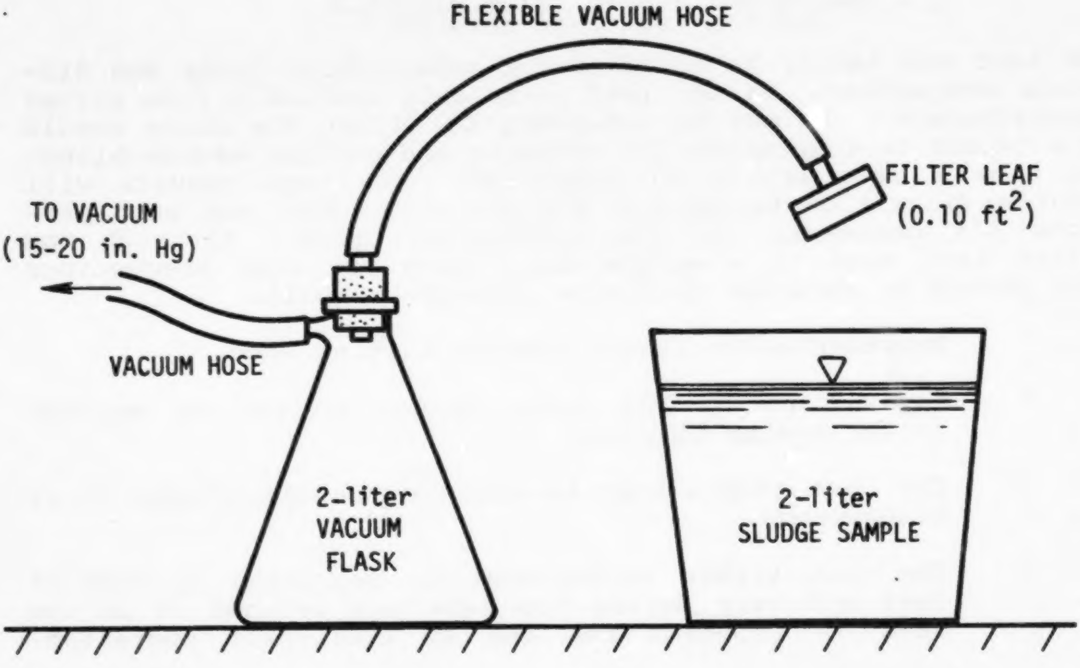

FLEXIBLE VACUUM HOSE
FILTER LEAF
(0.10 ft^2)
TO VACUUM
(15-20 in. Hg)
VACUUM HOSE
2-liter
VACUUM
FLASK
2-liter
SLUDGE SAMPLE

Figure 4.10-8. Filter leaf test apparatus.[2]

3. Bring leaf to vertical position and dry under vacuum for 3 min (or other predetermined time). This is the cake draining and drying part of the cycle.

4. Blow off cake for 1-1/2 min (this gives a total drum cycle of 6 min). To discharge the cake, disconnect the leaf and apply air (pressure not exceeding 2 psi).

5. Weigh cake, then dry and reweigh to determine percentage moisture. The filter rate (Y) in pounds/square foot per hour is computed:

$$Y = \frac{\text{dry weight sludge (g) x cycles/h}}{\text{453.6 x test leaf area}(\text{ft}^2)}$$

The test can easily be modified for other cycle times and discharge mechanisms. Filter leaf is readily available from filter manufacturers. It may be necessary to adjust the above result by a factor to compensate for scale-up and partial medium blinding over a long period of operation. The test results will provide filtration parameters for the form, dry, and wash portions (if necessary) of the filtration cycle. Although the filter leaf test is a simple one, there are some precautions that should be observed to ensure accurate results:

- Representative sludge samples must be used.
- Several (5 to 10) tests should be run to monitor filter medium blinding.
- The test sample must be agitated to ensure that it is homogeneous.
- The test filter vacuum must be regulated so that it does not vary during the test and so that it is the same as proposed for use in full-scale operation.

The filter leaf tests have been conducted for numerous industrial and municipal waste treatment applications, and the scale-up techniques are well established.[6] The filter area provided for in design should be for the peak sludge removal rate required, plus a 5 to 15 percent area allowance.

If large variations in solids handling capability are encountered, it is often more desirable to install two smaller filters than one large filter. In this way, when the solids amount decreases substantially over a long period, one of the units may be shut down; this will allow the other to operate at the proper submergence level and thereby to optimize performance. In addition, vendors recommend installation of a spare for uninterrupted plant operation.

4.10.3.4 Available Equipment--

Five types of vacuum filters are applicable for dewatering sludges from lime-based FGD systems: drum, belt, disk, horizontal belt, and pan.

The horizontal belt and pan vacuum filters are designed for the dewatering of quick-draining, coarse solids that cannot be retained on a vertical filter medium. They are also useful for recovering valuable chemicals by washing.

The disk vacuum filter, which provides the highest filtering surface area for the size of the equipment, is normally used to handle large volumes of slurry, as in mineral processing operations.

The rotary-drum vacuum filter is the most popular design. It is usually the least expensive filter, in dollars/square foot of filter area for a given application, that still permits cake washing to be accomplished. The disadvantage of the unit is that it is susceptible to medium blinding and wearing of the medium; this is because the scraper at the discharge point abrades the filter cloth. Replacement of the medium is time-consuming because it must be caulked and possibly wire-wound. The rotary filter can therefore be costly from a maintenance standpoint.

The belt filter (Figure 4.10-9) is an improved version of the rotary-drum filter. The filter medium is lifted from the drum after the dewatering portion of the cycle is completed and is passed over a small-diameter roller to effect cake removal. This rapid change in direction ensures a complete discharge of cake without the need of a scraper. Thus, the filter cloth life is comparatively long. After cake discharge, the medium is washed on both sides. This arrangement provides a clean medium for each filter cycle and prevents blinding, a particular advantage in the filtering of solids, such as gypsum, that tend to blind the medium. The installed cost of a belt filter, however, is approximately 30 percent higher than that of the equivalent size drum filter unit.[7] A comparison of filter costs is presented in Figure 4.10-10.

4.10.3.5 Existing Facilities--

The preferred methods of sludge disposal are ponding or the use of a special stabilizing process such as Calcilox (by Dravo Lime Corp.), Poz-O-Tec (by International Utility Conversion Systems, Inc.), or Chemfix; however, one utility company has installed filter equipment in a lime-based FGD system. The filter installation is at Paddy's Run No. 6 Unit (Louisville Gas & Electric Co.). This plant has two rotary-drum vacuum filters, each with 150-ft^2 filtering area and 10-tons/h sludge handling capacity. Twenty to 24 percent solids feed from a thickener is dewatered to 45 percent solids on nylon cloth medium, and the filter cake is disposed of on an offsite landfill area.

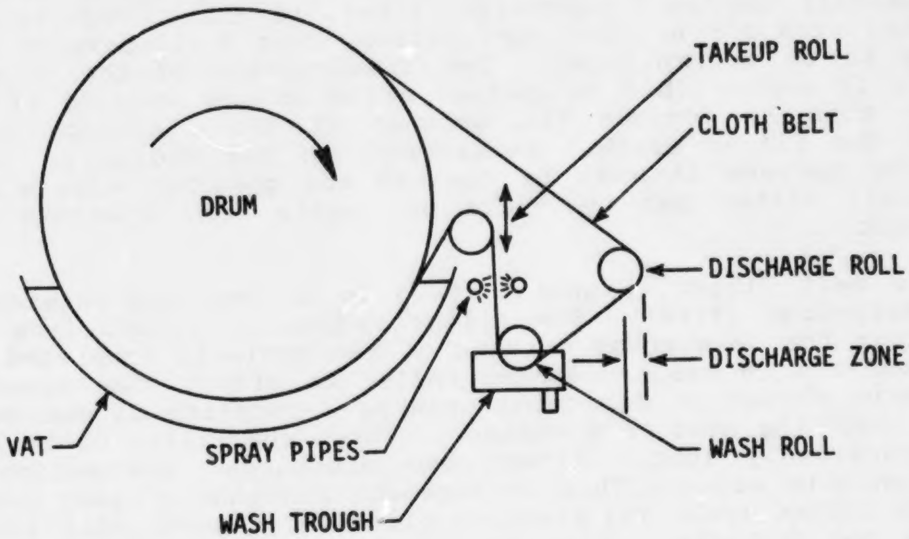

TAKEUP ROLL
CLOTH BELT
DRUM
DISCHARGE ROLL
DISCHARGE ZONE
VAT
SPRAY PIPES
WASH ROLL
WASH TROUGH

Figure 4.10-9. Cross section of a belt filter.

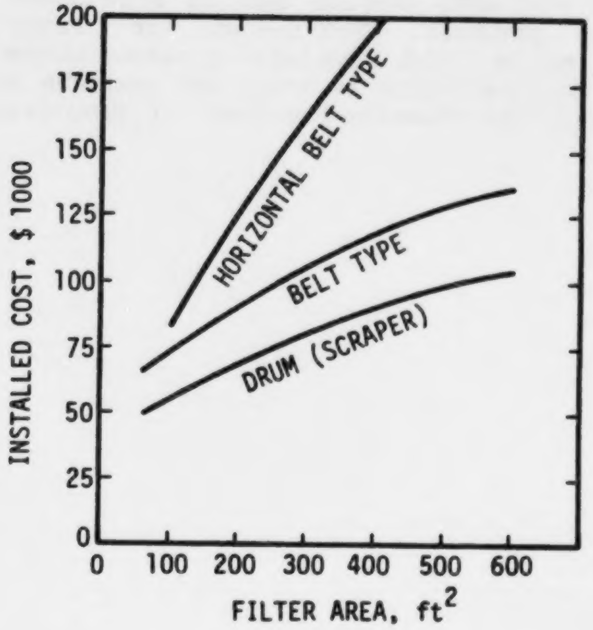


Figure 4.10-10. Filter costs (7).

Some utility plants (Conesville, Elrama, and Phillips Power Stations) have contracts for waste disposal with IUCS, (Philadelphia) to produce the environmentally acceptable Poz-O-Tec.[8] With this process (Figure 4.10-11), the partially dewatered slurry from the FGD system thickener is pumped to the stabilization system surge tank. The slurry is then pumped to a secondary thickener, if necessary, or directly to vacuum filters. The capacity of vacuum filters is 150 lb/ft^2 per h of 60 weight percent solids from 36 to 40 weight percent feed.[10] The filter cake is then mixed with hydrated lime, $Ca(OH)_2$, and silica, SiO_2, from the boiler fly ash; bottom ash is sometimes used as well. The resulting product, Poz-O-Tec, is light-weight, stronger than natural soils, and develops greater slope stability on landfill. Its permeability is very low and the volume is significantly less than the combined volume of untreated materials.[11]

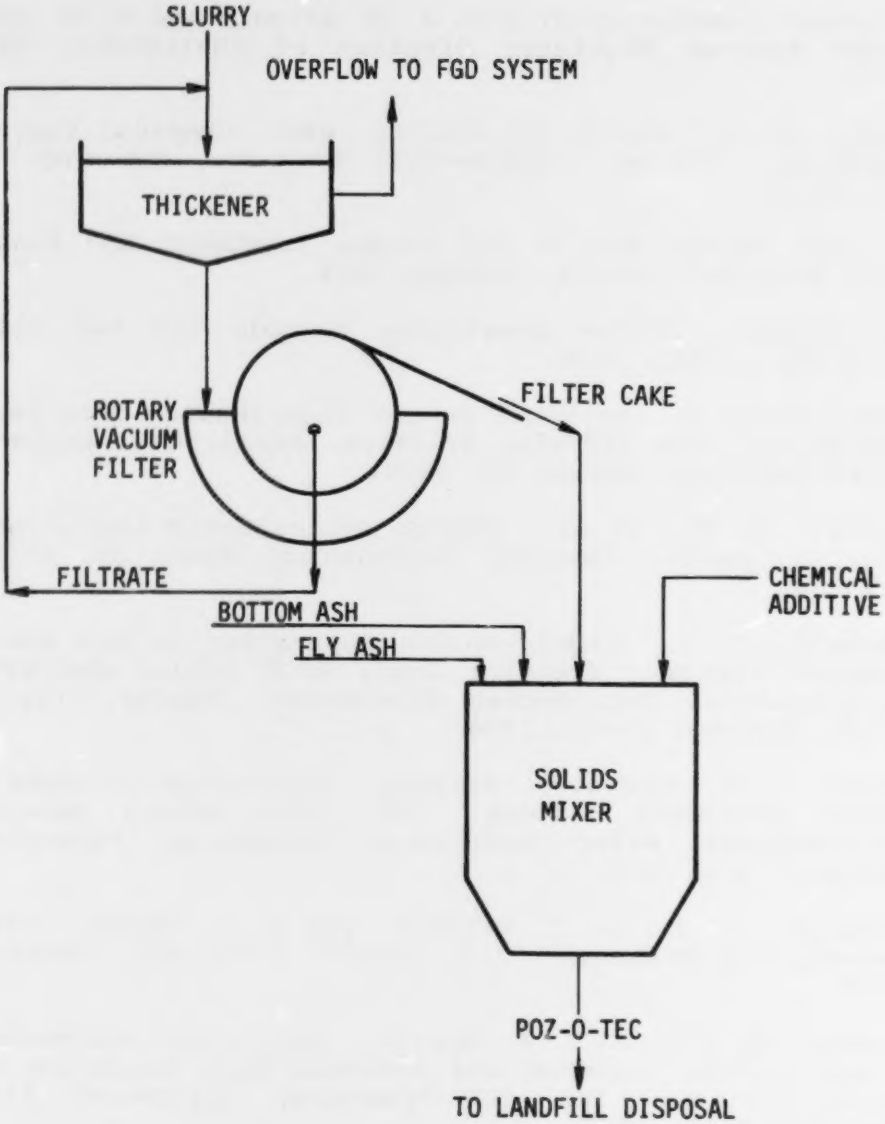

SLURRY
OVERFLOW TO FGD SYSTEM
THICKENER
ROTARY VACUUM FILTER
FILTER CAKE
FILTRATE
BOTTOM ASH
FLY ASH
CHEMICAL ADDITIVE
SOLIDS MIXER
POZ-O-TEC
TO LANDFILL DISPOSAL

Figure 4.10-11. Pox-O-Tec process.
Source: IUCS, Philadelphia, Pa.

REFERENCES

1. Personal communication with J. H. Wilhelm and R. W. Kobler, EIMCO Process Machinery Division of Envirotech, October 1977.

2. Perry, R. H., and C. H. Chilton, eds. Chemical Engineers' Handbook. 5th ed. McGraw-Hill Book Co., New York, 1973. pp. 19-93.

3. Process Design Manual for Sludge Treatment and Disposal. U.S. EPA-625/1-74-006, October 1974.

4. Envirotech. Sludge Dewatering Methods for FGD Cleaning Products. EPRI, 1978.

5. Rabb, David T. Selected Topics from Shawnee Test Facility Operation. EPA Industry Briefing, Research Triangle Park, North Carolina, August 29, 1978.

6. Tiller, F. M., et al. How to Select Solid Liquid Separation Equipment. Chemical Engineering, April 29, 1974, pp. 116-136.

7. Cornell, C. F. Liquid-solids Separation in Air Pollution Removal System. Preprint 2363, ASCE Annual and National Environmental Engineering Convention, Kansas City, Missouri, October 21-25, 1974.

8. Heden, S. D., and J. H. Wilhelm. Dewatering of Power Plant Waste Treatment Sludges. In: 36th Annual Meeting of International Water Conference, Pittsburgh, Pennsylvania, November 4-6, 1975.

9. Minnick, L. J., W. C. Webster, and C. L. Smith. Lime-Fly Ash-Sulfite Mixtures. U.S. Patent 3,785,840, January 15, 1974.

10. Boston, D. L., and J. E. Martin. Full-scale FGD Waste Disposal at the Columbus and Southern Ohio Electrics Conesville Station. In: FGD Symposium, Hollywood, Florida, November 8-11, 1977.

11. Mullen, H., L. Ruggiano, and S. Taub. The Physical and Environmental Properties of Poz-O-Tec. In: Engineering Foundation Conference on Disposal of Flue Gas Desulfurization Solids, Hueston Woods, Cincinnati, October 19, 1976.

CONTENTS

4.11 STACK GAS REHEATING

Page

4.11.1 Introduction 4.11-1

4.11.2 Reasons for Reheat 4.11-1

- 4.11.2.1 Prevention of Downstream Condensation and Sebsequent Corrosion 4.11-1
- 4.11.2.2 Prevention of a Visible Plume 4.11-3
- 4.11.2.3 Plume Rise and Dispersion of Pollutants 4.11-3

4.11.3 Methods of Stack Gas Reheat 4.11-4

- 4.11.3.1 In-line Reheat 4.11-4
- 4.11.3.2 Direct-firing Reheat 4.11-6
- 4.11.3.3 Indirect Hot Air Reheat 4.11-8
- 4.11.3.4 Bypass Reheat 4.11-8
- 4.11.3.5 Exit Gas Recirculation Reheat 4.11-8

4.11.4 Reheat Requirement for Prevention of Downstream Condensation 4.11-11

- 4.11.4.1 In-line Reheat 4.11-11
- 4.11.4.2 Indirect Hot Air Reheat 4.11-13
- 4.11.4.3 Direct-firing Reheat 4.11-15

4.11.5 Reheat Requirement for Normal Operation and Prevention of Visible Plume 4.11-17

- 4.11.5.1 In-line Reheat 4.11-17
- 4.11.5.2 Indirect Hot Air Reheat 4.11-18
- 4.11.5.3 Direct-firing Reheat 4.11-18

4.11.6 Reheat Requirement for Enhancement of Plume Rise and Dispersion of Pollutants 4.11-19

4.11.7 Analysis of Bypass Reheat 4.11-21

4.11.8 No Reheat 4.11-22

4.11.9 Acid Condensation and Reheat 4.11-23

4.11.10 Selecting Optimum Sources of Energy for Gas Reheating 4.11-23

CONTENTS (continued)

Page

4.11.11 Existing Systems 4.11-24

4.11.11.1 Hawthorn (Kansas City Power and Light) 4.11-24
4.11.11.2 Four Corners (Arizona Public Service) 4.11-27
4.11.11.3 Colstrip (Montanta Power) 4.11-27
4.11.11.4 Phillips Stations (Duquesne Light & Power) 4.11-27
4.11.11.5 Elrama Station (Duquesne Light & Power) 4.11-27
4.11.11.6 Bruce Mansfield (Pennsylvania Power Co.) 4.11-27
4.11.11.7 Paddy's Run 6 (Louisville Gas and Electric Co.) 4.11-28

4.11.12 Recommendations 4.11-28

References 4.11-29

Bibliography 4.11-30

4.11 STACK GAS REHEATING

4.11.1 Introduction

One of the major drawbacks to wet scrubbing methods for cleaning stack gas is unwanted cooling of the gas and its saturation with water vapor as it exits the scrubber. The several problems that result from this have led to reheating of the gas in most of the operating or planned FGD scrubber installations. The reheat system can be located directly above the mist eliminator (Figure 4.11-1) or in the horizontal duct leading to the stack. Hot air or bypassed gas may also be injected downstream from the mist eliminator.

Before dealing with the subject of reheat, it is important to know the following terminology and relationships:

Absolute humidity: The amount (in pounds) of water vapor carried by one pound of dry air.

Percentage relative humidity: The partial pressure of water vapor in air divided by the vapor pressure of water at a given temperature.

Dew point or saturation temperature: The temperature at which a given mixture of water vapor and air is saturated.

Wet-bulb temperature: The equilibrium temperature attained by a water surface when the rate of heat transfer to the surface equals the rate of heat transfer from the surface because of the liquid evaporation.

4.11.2 Reasons for Reheat

A major question in designing wet scrubbing systems is whether or not scrubbed gas should be reheated, and if so, how to do it. The reasons usually advanced for reheating are as follows:

(1) To prevent downstream condensation and subsequent corrosion, and either

(2) To prevent emission of a visible plume (the stack gas temperature required ranges from 180° to 220°F), or

(3) To enhance plume rise and dispersion of pollutants (stack gas temperature required is above 220°F)

4.11.2.1 Prevention of Downstream Condensation and Subsequent Corrosion--

At power plants, the flue gas exits the wet scrubber in a saturated condition at about 125°F. The gas also contains mist

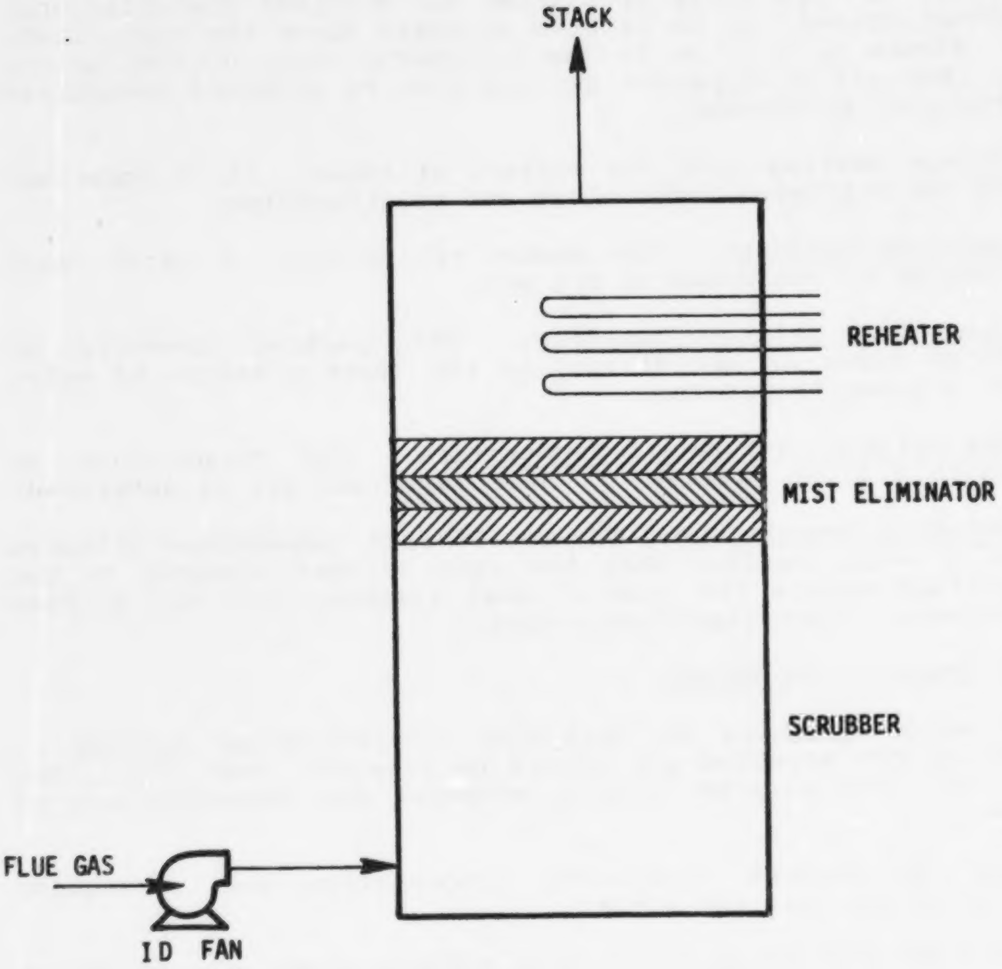

STACK
REHEATER
MIST ELIMINATOR
SCRUBBER
FLUE GAS
ID FAN

Figure 4.11-1. Reheat system location.

droplets, the amount depending on the efficienty of the mist eliminator. If the gas is not reheated, an induced-draft (ID) fan downstream from the scrubber will run wet, and entrained fly ash and slurry will be able to deposit on the wet surface of the fan blades. Removal of the resulting solid deposits from the fan is troublesome and expensive. Although there has been improvement in this area, corrosion problems in the ducts and stack are still severe in most cases. In some cases, deposits of solids on the ID fan, ductwork, and the inside walls may absorb residual SO_2 from the flue gas. This could result in highly acidic conditions capable of corroding fan blades and ducting and damaging the stack coating.

4.11.2.2 Prevention of a Visible Plume (Normal Operation, Reheat to 180° to 220°F Range)--

In the absence of stack gas reheat, "acid rain" can occur. Acid rain is formed by the condensation of droplets and their absorption of residual SO_2 in the plume. Since the stack gas contains more water vapor than that from normal plant operation, formation of a steam plume can occur more easily. This is a major consideration in some situations, especially if the plant is in a densely populated area and the neighbors are sensitive to visible emissions. To avoid a visible plume, the gas is reheated between 100° to 220°F.

4.11.2.3 Plume Rise and Dispersion of Pollutants (Reheat to above 220°F)--

A plume may be several miles from the plant before it finally reaches the ground. Ground-level concentration is of concern to regulatory authorities who set maximum ambient levels.

To achieve plume rise and dispersion of pollutants, the gas can be reheated to 220° to 300°F, which in some cases is the same as the scrubber inlet temperature. This practice is especially prevalent in Japan, where among the four major scrubber installations operated by utilities, the reheat level at one is 250°F and at the other three, 290°F. This extra heating accounts for as much as 5 percent of the total fuel costs, but is considered justifiable because it promotes good community relations.

The Federal SO_2 regulation for new coal-fired plants currently allows a maximum emission of 1.2 lb SO_2/million Btu. The regulation does not mention the degree of reheat or, for that matter, the height of the stack. Thus, as far as the SO_2 emission regulation is concerned, the plant operator can save money by not reheating the gas if he is willing to accept the other trade-offs.

Ambient standards, however, apply to all sources; it is the responsibility of the states to enforce compliance. If scrubbers are to be installed in a given plant, it becomes a matter, (theoretically at least) of predicting whether or not the ambient air standard will be met at the proposed degree of reheat. If the prediction (based on plume dispersion models) indicates that the ambient standard will be exceeded, then the degree of reheat or the stack height must be increased, or the SO_2 emissions decreased still further. The matter of reheat, however, does not seem to have come up in permit hearings. Control of the degree of reheat, as applied to the prediction of ambient concentration, is a refinement that apparently has not yet come into wide use in the United States.

4.11.3 Methods of Stack Gas Reheat

The following methods can be used to increase the temperature of the gas from a wet scrubber.

(1) In-line reheat
(2) Direct-firing reheat
(3) Indirect hot air reheat
(4) Bypass reheat
(5) Exit gas recirculation reheat

Method (5) is not used commercially for lime scrubbing applications.

4.11.3.1 In-line Reheat--

The most popular system is a heat exchanger installed in the flue gas duct following the scrubber mist eliminator. The in-line reheater is simple in design and installation as shown in Figure 4.11-2; however, it is difficult to maintain because of corrosion and plugging in the tube bundles.

The tubes are usually arranged in banks. Since deposits on the tubes reduce the heat transfer considerably and cause corrosion, soot blowers are normally installed between the banks. Corrosion has been a problem, and even expensive alloys have been unsatisfactory under some conditions. A large number of materials have been tested in TVA's Colbert pilot plant, including Cor-Ten A, Cor-Ten B, Incoloy 825, Inconel 625, various 300 series stainless steels, and Hastelloy C-276. This is further discussed in Section 4.12.7. When used in lime scrubbing systems, 304 SS and 316 SS have sometimes failed within a few months. In contrast, carbon steel tubes have given acceptable service at some installations for up to 5 years.

No good explanation of this is available. Obviously some differences in operating conditions are responsible, but it is not clear what they are. Factors postulated to be significant

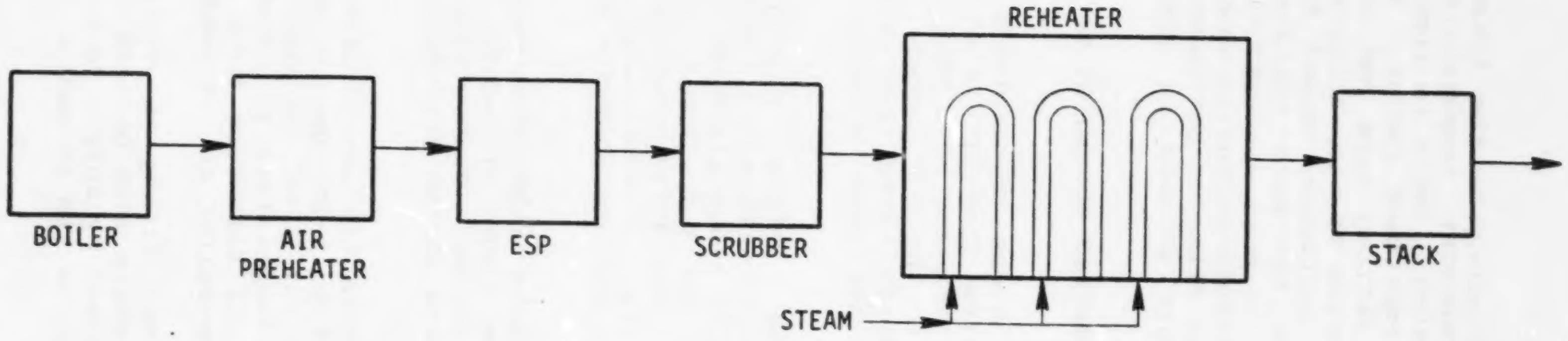

BOILER
AIR PREHEATER
ESP
SCRUBBER
REHEATER
STEAM
STACK

Figure 4.11-2. In-line reheat system.

include the amount of mist impinging on the tubes, distance between the mist eliminator and reheater, temperature inside the tubes, and adequacy of soot blowing. There is some indication that soot blowing is the most important factor. Much of the corrosion of tubes is of the pitting type and occurs under deposits on the tubes. The corrosion of high-alloy materials is generally attributed to stress corrosion caused by chloride. Stress corrosion causes failure far more rapidly than does general corrosion. Carbon steel is more susceptible to general corrosion but more resistant to stress corrosion than high-alloy materials, and vice versa, in the reheater environment. Carbon steel reheaters thus may be more durable in operation than stainless steel reheaters.

In-line reheat can be classified according to the heating medium (steam or hot water).

Steam in-line reheat--Inlet steam temperatures range from 420° to 720°F, and steam pressures from 115 to 450 psig. The main problems with this type of reheater have been corrosion of the heating tubes and plugging in the tube banks. Superheated steam requires a larger heat-transfer area than saturated steam does, since it involves gas-to-gas heat transfer. Saturated steam is preferred.

Hot water in-line reheat--The system configuration is similar to that of the steam in-line reheaters, except that hot water is the heating medium. Inlet temperature of the hot water ranges from 250° to 350°F, and the temperature drop over the heat exchanger is 70° to 80°F. The inlet pressure of the hot water ranges from 15 to 120 psig. Finned tubes are usually required for better heat transfer and soot blowers are needed to clean the tubes.

Corrosion problems with these reheaters have been less severe possibly because of the lower operating temperature. Plugging, however, has been a major maintenance item at Lawrence Station because of the finned tubes in the heat exchanger.

4.11.3.2 Direct-firing Reheat--

This type of system eliminates the use of heat exchangers. As shown in Figures 4.11-3a and 4.11-3b, gas or oil is burned and the combustion product gas (at 1200° to 3000°F) is mixed with the flue gas to raise its temperature to between 150° and 300°F. In Japan, practically all scrubbers have direct-fired oil reheat, and in most cases low-sulfur oil is used.

The main problem with direct firing is availability and cost of gas and oil. In Japan, where most boilers burn oil, the overall oil requirement is increased by only 2 to 5 percent. In the United States, however, coal is the principal fuel; oil or

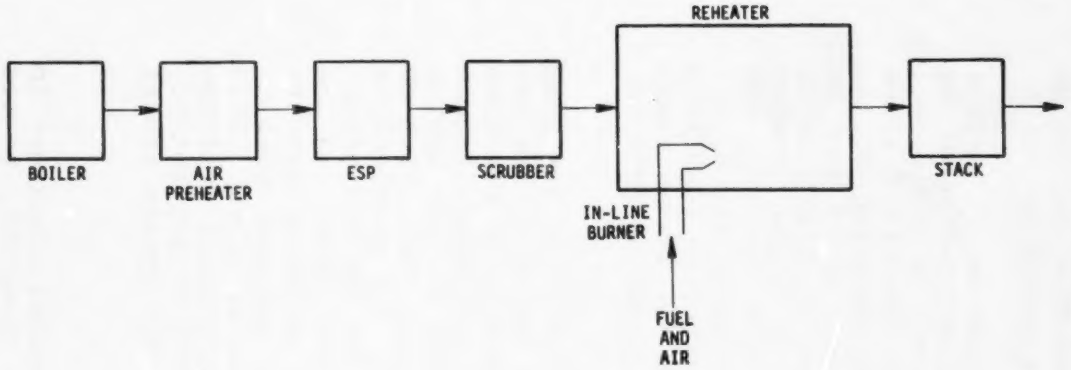

REHEATER
BOILER
AIR PREHEATER
ESP
SCRUBBER
STACK
IN-LINE BURNER
FUEL AND AIR

Figure 4.11-3a. Direct-firing reheat system using in-line burner.

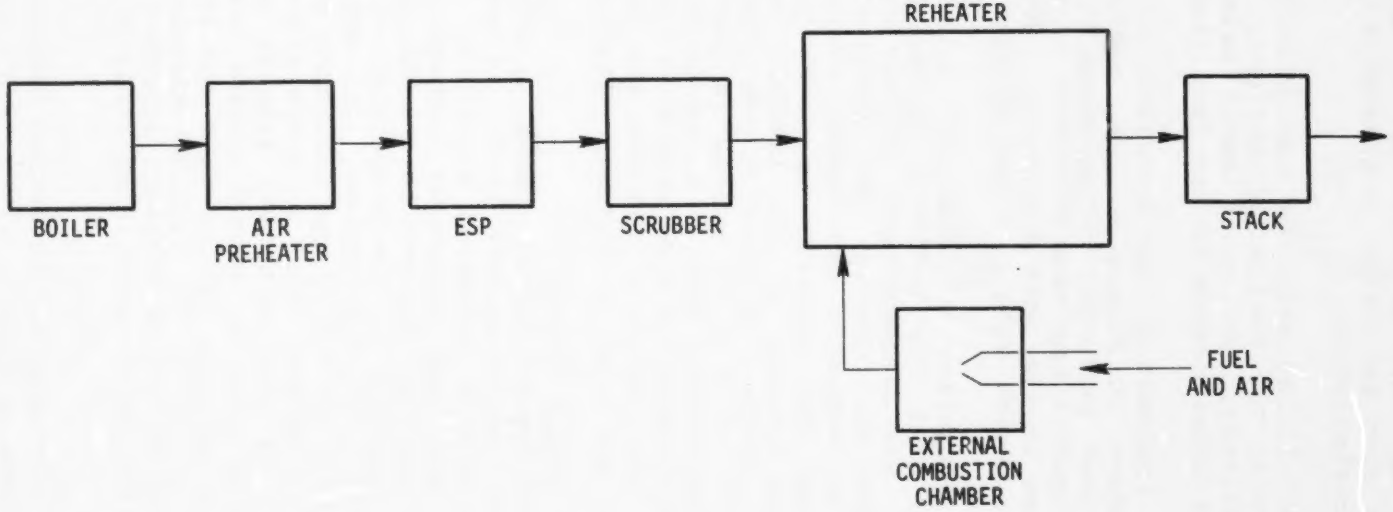

REHEATER
BOILER
AIR PREHEATER
ESP
SCRUBBER
STACK
FUEL AND AIR
EXTERNAL COMBUSTION CHAMBER

Figure 4.11-3b. Direct-firing reheat system using external combustion chamber.

gas would not only be difficult to obtain in some situations, but would also be costly and usually require a new storage or pipeline installation.

Direct firing requires some care in mixing the hot combustion gas with the cool scrubbing gas. If mixing is not carried out effectively, hot spots could develop downstream from the heater and cause damage to the duct lining.

4.11.3.3 Indirect Hot Air Reheat--

As shown in Figure 4.11-4, ambient air is heated by an external heat exchanger using steam to temperatures of 350° to 450°F. Finned tubes made of carbon steel are arranged in two to three banks in the heat exchanger. Hot air and flue gas may be mixed by a device such as a set of nozzles or a manifold.

The advantage of indirect hot air reheat over in-line reheat is that the indirect system involves no corrosion or plugging. Its disadvantages include the need for an additional fan for hot air blowing, the relatively large amount of space required to retrofit the reheat system to an existing boiler system, and the increase in stack gas volume, which may be undesirable because of the limited capacities of existing ID fans and stacks. Another disadvantage is its higher energy consumption; this extra energy is needed to heat air from the ambient temperature level. An advantage that offsets the higher energy requirement to some extent is that the dilution resulting from the air addition reduces the incidence of steam plume formation and also presumably gives better plume dispersion.

4.11.3.4 Bypass Reheat--

In the bypass reheat system, a portion of hot flue gas from the boiler (approximately 300°F) is taken off ahead of the wet scrubbing system, bypassed around it, and mixed with the flue gas that has been processed through the wet scrubber (Figure 4.11-5). The limiting conditions for application of this system are determined by (1) the properties of the boiler fuel, such as heating value, sulfur content, and ash content; (2) particulate control (ESP) preceding the scrubbing system; (3) the characteristics of flue gas, such as temperature and flow rates; (4) the efficiency of the scrubbing system; and (5) emission regulations. Provision of enough reheat sometimes requires that as much as 40 percent of the flue gas bypass the scrubber. This requires very high SO_2 removal efficiency and lenient performance standards. A performance standard requiring 90 percent SO_2 removal efficiency would completely rule out the bypass reheat option.

4.11.3.5 Exit Gas Recirculation Reheat--

As shown in Figure 4.11-6, a portion of heated stack gas in the exit gas recirculation reheat system is diverted, heated

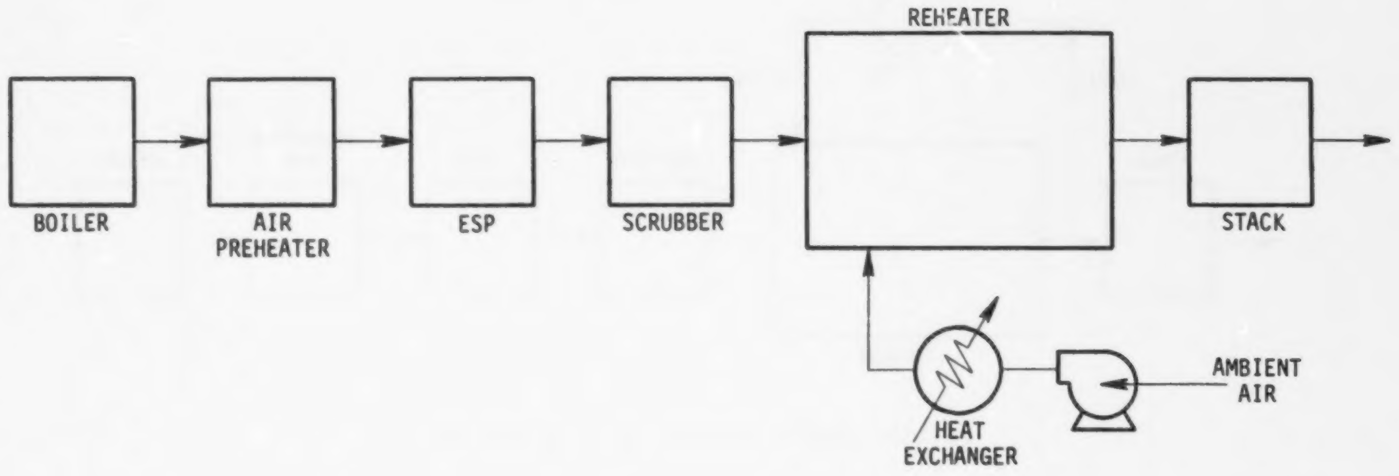

REHEATER
BOILER
AIR PREHEATER
ESP
SCRUBBER
STACK
AMBIENT AIR
HEAT EXCHANGER

Figure 4.11-4. Indirect hot air reheat system.

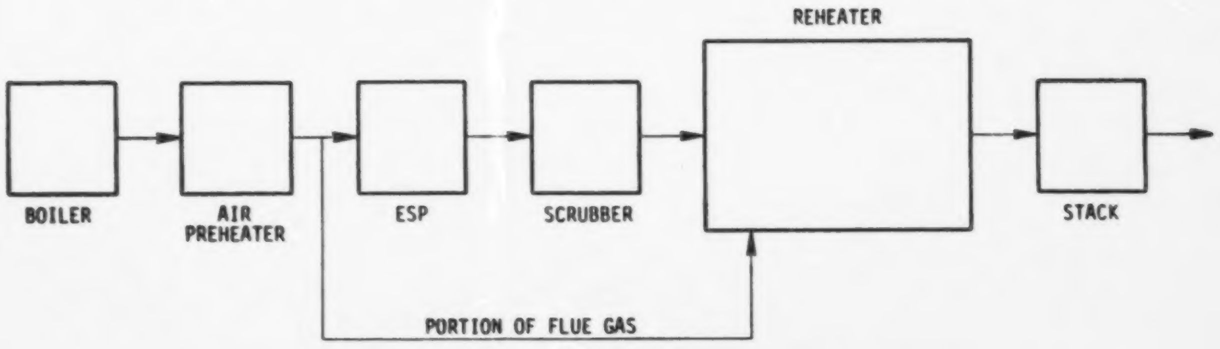

REHEATER
BOILER
AIR PREHEATER
ESP
SCRUBBER
STACK
PORTION OF FLUE GAS

Figure 4.11-5. Bypass reheat system.

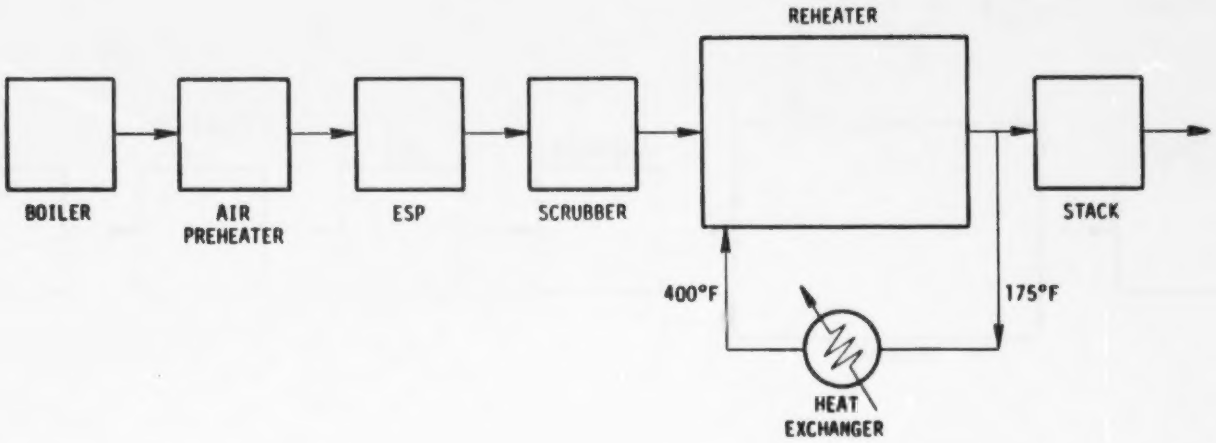

REHEATER
BOILER
AIR PREHEATER
ESP
SCRUBBER
STACK
400°F
175°F
HEAT EXCHANGER

Figure 4.11-6. Reheat by exit gas recirculation.

further to approximately 400°F by an external heat exchanger, and injected back into the flue gas from the wet scrubber. As opposed to an indirect hot air reheat system, this system does not increase the total stack gas flow rate, and the reheat operation is less influenced by ambient air conditions. A major advantage of this system is that the tubes are not exposed to mist droplets. Its disadvantage is its high capital cost.

4.11.4 Reheat Requirement for Prevention of Downstream Condensation

The reheat requirement to prevent downstream condensation can be estimated by making a heat balance around the downstream system, including the stack. Condensation takes place when the vapor pressure of water in the stack gas exceeds the saturation value at the specific stack gas temperature and pressure. To prevent condensation, (1) the gas temperature is raised above the dew point (usually 125°F) or (2) the gas is diluted at the same temperature with a gas having lower moisture content so the vapor pressure of water in the stack gas decreases. A combination of both measures can also be used.

4.11.4.1 In-line Reheat--

A schematic of the heat balance around the downstream system, including an in-line reheater, is shown in Figure 4.11-7. The flue gas from a wet scrubber is usually saturated with water vapor. The gas is heated by steam or hot water, passed through the ducts and stack, and emitted to the atmosphere. Gas temperature at the top of the stack should be at dew point or higher to prevent condensation before emission. Because an increase in water vapor pressure results from evaporation of the mist carried over from the scrubber, the dew point at the top of the stack is slightly higher than the temperature of gas exiting the scrubber. The minimum heat requirement from steam or hot water is given in Equation 4.11-1.

$$\text{Heat input} = \text{Heat required to raise gas to its dew point} + \text{Heat loss from ducts} + \text{Heat loss from stack} + \text{Heat required to evaporate mist carryover} - \text{Heat gain due to fan}$$

$$Q = \frac{F\ Cpm}{379}(T_d - T_1) + Q_{LD} + Q_{LS} + L - Q_F \qquad \text{(Eq. 4.11-1)}$$

where,

Q = minimum heat requirement from steam or hot water, Btu/h

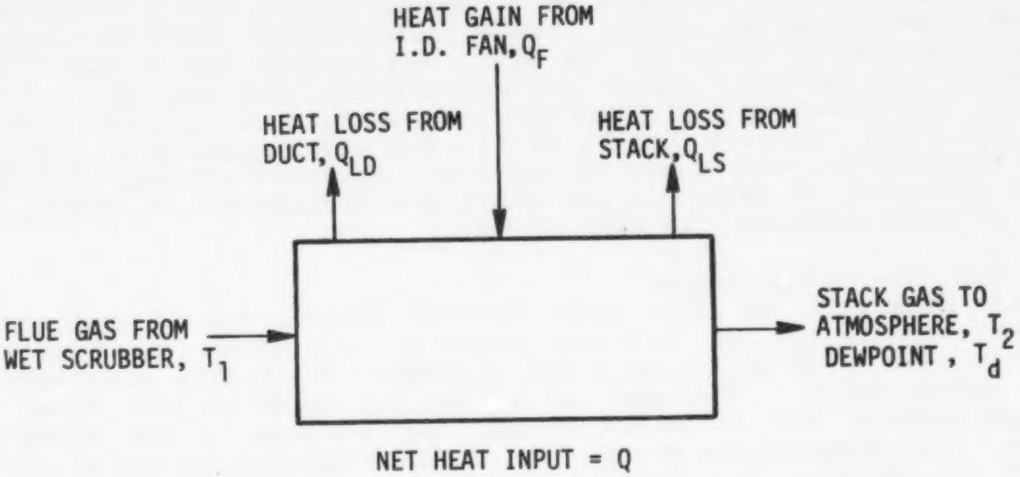

HEAT GAIN FROM
I.D. FAN, Q_F
HEAT LOSS FROM
DUCT, Q_{LD}
HEAT LOSS FROM
STACK, Q_{LS}
FLUE GAS FROM
WET SCRUBBER, T_1
STACK GAS TO
ATMOSPHERE, T_2
DEWPOINT, T_d
NET HEAT INPUT = Q

Figure 4.11-7. Schematic of heat balance around downstream system with in-line reheater.

C_{pm} = mean heat capacity of flue gas at constant pressure, Btu/(lb mol)°F

F = Flue gas flow rate, scfh

T_d = dew point of stack gas at top of stack, °F (usually 125°F)

T_1 = temperature of flue gas exiting wet scrubber, °F

Q_{LD} = heat loss from ducts, Btu/h

Q_{LS} = heat loss from stack, Btu/h

L = heat required to evaporate mist carryover, Btu/h

Q_F = heat gain from ID fan, Btu/h

For estimation purposes, the overall heat-transfer coefficient (the thermal conductivity) can be assumed to be 10 Btu/(ft)^2(°F)(h) for steam-gas (condensing steam) heat exchange and to be 6 Btu/(ft)^2(°F)(h) for hot water-gas heat exchange. Because of the very small difference between T_d and T_1, the amount of heat required to raise gas to its dew point will be very small. The method for calculating dew point is shown in the Material Balance Section of this book. The constant 379 is the conversion factor for obtaining the volume of 1 lb-mol of gas at 1 atm and 60°F. The values of Q_{LD}, Q_F, and Q_{LS} vary, depending on the specific situation; Q_{LD} could be significant, depending on whether the duct is insulated, the length of duct, and the difference between stack gas temperature and ambient air temperature.

The value Q_{LS} depends on the height of the stack, the materials of construction, and the difference between stack gas temperature and ambient air temperature. A study by the Tennessee Valley Authority (TVA) quoted a temperature drop of 4°F in a 300-ft stack.[2] In modern stacks, with an annular space between the stack and liner, the temperature drop should not be significant.

The heat (L) required to evaporate mist carryover depends upon the amount of carryover from the mist eliminator to the reheater.

4.11.4.2 Indirect Hot Air Reheater--

Figure 4.11-8 is a schematic of the heat balance around the stack gas downstream system, including an indirect hot air reheater. In this system, the flue gas from a wet scrubber is heated by addition of hot air. This results in a decrease of water vapor pressure in the stack gas as well as a drop in stack gas temperature. The minimum heat requirement from steam can be obtained from equations 4.11-2 and 4.11-3:

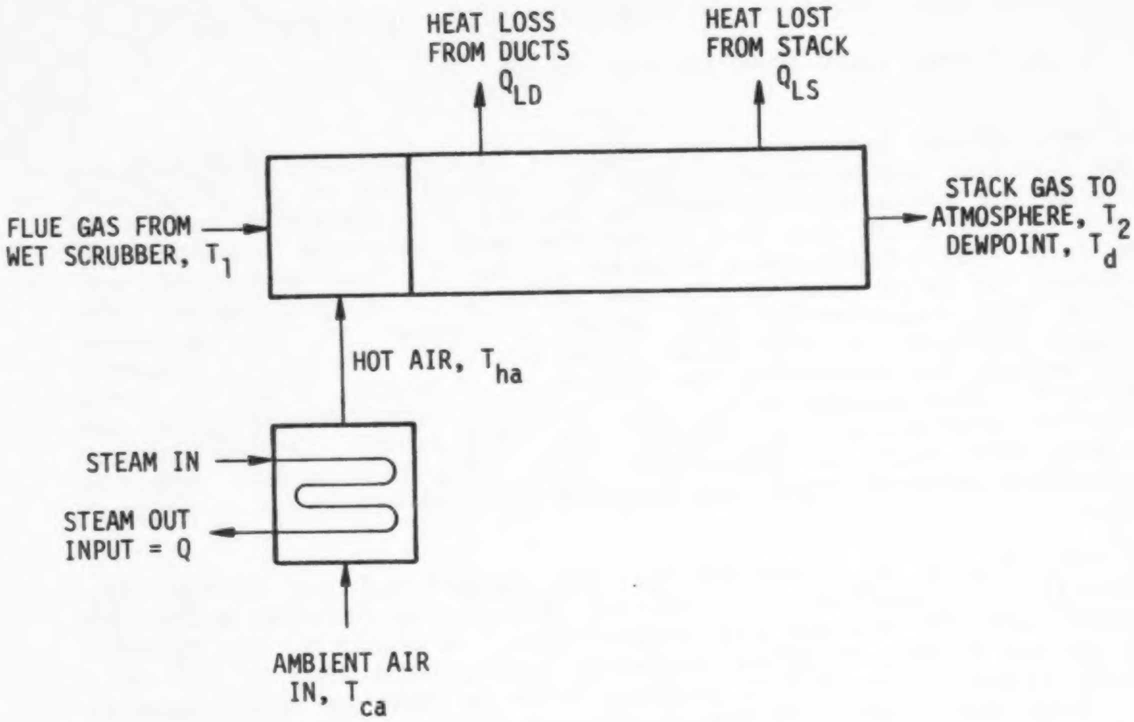

HEAT LOSS FROM DUCTS Q_{LD}
HEAT LOST FROM STACK Q_{LS}
FLUE GAS FROM WET SCRUBBER, T_1
STACK GAS TO ATMOSPHERE, T_2
DEWPOINT, T_d
HOT AIR, T_{ha}
STEAM IN
STEAM OUT
INPUT = Q
AMBIENT AIR IN, T_{ca}

Figure 4.11-8. Schematic of heat balance around downstream system with indirect hot air reheater.

$$\begin{matrix}\text{Heat required}\\ \text{to raise gas}\\ \text{to its dew}\\ \text{point}\end{matrix} + \begin{matrix}\text{Heat}\\ \text{loss}\\ \text{from}\\ \text{ducts}\end{matrix} + \begin{matrix}\text{Heat}\\ \text{loss}\\ \text{from}\\ \text{stack}\end{matrix} + \begin{matrix}\text{Heat}\\ \text{required}\\ \text{to evap-}\\ \text{orate mist}\\ \text{carryover}\end{matrix} = \begin{matrix}\text{Heat}\\ \text{gain}\\ \text{from}\\ \text{heated}\\ \text{air}\end{matrix}$$

$$\frac{FC_{pm}}{379}(T_d - T_1) + Q_{LD} + Q_{LS} + L = \frac{F_aC_{pa}}{379}(T_{ha} - T_d) \qquad \text{(Eq. 4.11-2)}$$

$$\text{Net heat input} = \begin{matrix}\text{Heat required by}\\ (F_a)\text{ amount of ambient}\\ \text{air to reach temperature } T_{ha}\end{matrix}$$

$$Q = \frac{F_aC_{pa}}{379}(T_{ha} - T_{ca}) \qquad \text{(Eq. 4.11-3)}$$

where,

F_a = ambient air flow rate, scfh

C_{pa} = specific heat of air, Btu/(lb-mol)°F

T_{ha} = temperature of hot air, °F

T_{ca} = temperature of ambient air, °F

and the other symbols are as previously defined.

In this case, Equation 4.11-2 is used to determine the temperature of hot air (Tha), then Equation 4.11-3 is used to determine the net heat input.

4.11.4.3 Direct-firing Reheat--

Figure 4.11-9 is a schematic of the heat balance around the stack gas downstream system; it includes a direct combustion reheater. Natural gas or low-sulfur fuel oil may be burned in the combustion chamber. The minimum heat requirement, Q, can be obtained from the following equations:

$$\begin{matrix}\text{Heat required}\\ \text{to raise gas}\\ \text{to its dew}\\ \text{point}\end{matrix} + \begin{matrix}\text{Heat}\\ \text{required}\\ \text{to evap-}\\ \text{orate}\\ \text{mist}\\ \text{carry-}\\ \text{over}\end{matrix} = \begin{matrix}\text{Net latent heat}\\ \text{of combustion}\\ \text{product gas}\\ \text{between tem-}\\ \text{peratures } T_g\\ \text{and } T_d\end{matrix} - \begin{matrix}\text{Heat}\\ \text{loss}\\ \text{from}\\ \text{ducts}\end{matrix} + \begin{matrix}\text{Heat}\\ \text{gain}\\ \text{from}\\ \text{fan}\end{matrix} - \begin{matrix}\text{Heat}\\ \text{loss}\\ \text{from}\\ \text{stack}\end{matrix}$$

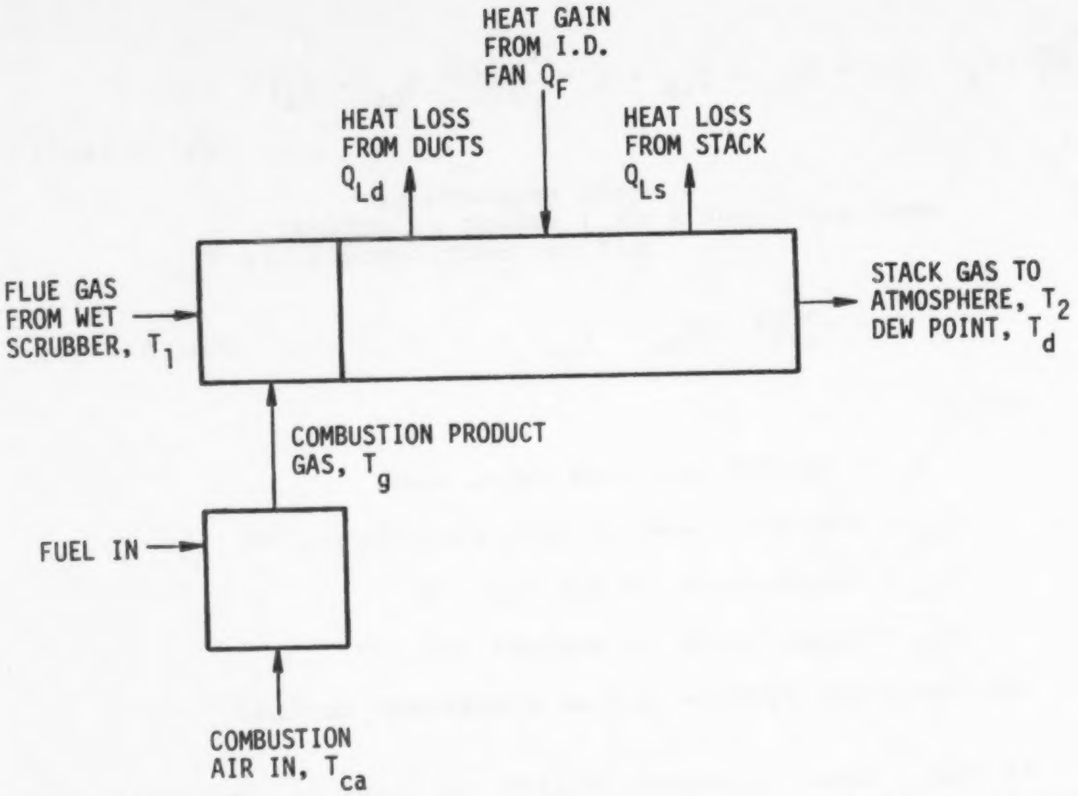

HEAT GAIN FROM I.D. FAN Q_F
HEAT LOSS FROM DUCTS Q_{Ld}
HEAT LOSS FROM STACK Q_{Ls}
FLUE GAS FROM WET SCRUBBER, T_1
STACK GAS TO ATMOSPHERE, T_2
DEW POINT, T_d
COMBUSTION PRODUCT GAS, T_g
FUEL IN
COMBUSTION AIR IN, T_{ca}

Figure 4.11-9. Schematic of heat balance around downstream system with direct combustion reheater.

$$\frac{FC_{pm}}{379}({}_T{}^d - T_1) + \quad L = \frac{F_gC_{pg}}{379}(T_g - T_d) - Q_{LD} + Q_F - Q_{LS}$$

(Eq. 4.11-4)

(Net heat input) = (Fuel consumption rate) x (Heating value of fuel)

$$Q = \quad q \quad x \quad v$$

(Eq. 4.11-5)

where,

F_g = combustion product gas flow rate, scfh

C_{pg} = specific heat of combustion product gas, Btu/(lb-mol)°F

T_g = temperature of combustion product gas, °F

q = fuel consumption rate, lb/h

v = heating value of fuel, Btu/lb

and the other symbols are as previously defined.

4.11.5 Reheat Requirement for Normal Operation and Prevention of Visible Plume

The section explains the methods for determining the required heat that are currently applied in most reheat installations. For normal operation and prevention of visible plume, the temperature desired at the top of the stack is selected by the designer. It is usually between 125° and 220°F. The reheat requirement for normal operation and prevention of visible plume can be estimated by making heat balances as follows:

4.11.5.1 In-line Reheat--

Minimum heat required	=	Heat required to raise gas from temperature T_1 to T_2	+	Heat loss from ducts	-	Heat gain due to fan	+	Heat loss from stack	+	Heat required to evaporate mist carryover

$$A = \frac{FC_{pm}}{379}(T_2 - T_1) + Q_{LD} - Q_F + Q_{LS} + L$$

(Eq. 4.11-6)

where,

A = minimum heat required

T_2 = stack gas temperature at the top of the stack.

All other symbols have been defined earlier.

4.11.5.2 Indirect Hot Air Reheat--

The computation here is more complicated than that for in-line reheat, since the stack gas is diluted with hot air.

Heat required to raise gas temperature from T_1 to T_2 + Heat required to evaporate mist carryover = Heat required by F_a amount of ambient air to reach temperature T_{ha} from T_1 - Heat loss from ducts + Heat gain due to fan - Heat loss from stack

$$\frac{FC_{pm}}{379}(T_2 - T_1) + L = \frac{F_a C_{pa}}{379}(T_{ha} - T_1) - Q_{LD} + Q_F - Q_{LS}$$

(Eq. 4.11-7)

Net heat input = Heat required by F_a amount of ambient air to reach temperature T_{ha}

$$Q = \frac{F_a C_{pm}}{379}(T_{ha} - T_{ca})$$

(Eq. 4.11-8)

4.11.5.3 Direct-firing Reheat--

Heat required to raise gas temperature from T_1 to T_2 + Heat required to evaporate mist carryover = Net latent heat of combustion product gas between temperatures T_g and T_2 - Heat loss from ducts + Heat gain due to fan - Heat loss from stack

$$\frac{FC_{pm}}{379}(T_2 - T_1) + L = \frac{F_g C_{pg}}{379}(T_g - T_2) - Q_{LD} + Q_F - Q_{LS}$$

(Eq. 4.11-9)

$$\text{(Net heat input)} = \text{(Fuel consumption rate)} \times \text{(Heating value of fuel)}$$

$$Q = q \times v$$

(Eq. 4.11-10)

All symbols used in the above equations have been defined earlier.

4.11.6 Reheat Requirement for Enhancement of Plume Rise and Dispersion of Pollutants

Use of a wet scrubber for stack gas desulfurization without reheat could result in poor plume rise and poor dispersion characteristics, which in turn could cause undesirably high ground-level concentrations of other pollutants, such as oxides of nitrogen. The computation of reheat requirements is very complicated because it requires a quantitative analysis of plume behavior in the atmosphere, which is a function of such variables as meteorological conditions, stack size, and characteristics of the stack gas at the emission point. For further details, refer to the report Stack Gas Reheat for Wet Flue Gas Desulfurization Systems, prepared by the Batelle Columbus Laboratories for Electric Power Research Institute (EPRI).[1]

To achieve dispersion of pollutants, the desired temperature at the top of the stack should be above 220°F. No installation in the United States provides that amount of reheat, although some Japanese installations reheat to as high as 290°F.

In the Battelle study, a family of curves was developed using mathematical models that predict maximum ambient concentrations under any given conditions. As shown in Figure 4.11-10, each curve represents a given percent of SO_2 removal from the gas; if nothing else were changed, this would also be the percent reduction in ambient concentration, because ground concentration is directly proportional to the amount of SO_2 emitted from the stack. Since the scrubbed gas will have a lower temperature (unless reheated to scrubber inlet temperature), the reduction in ambient concentration will be a lower value.

The curves show that as SO_2 removal increases, the degree of reheat has less and less effect on reduction in ground-level concentration. At 90 percent removal, for example, even without reheat the maximum ambient air concentration is reduced by 83 percent; at about 40 percent removal, however, there is no reduction in the ambient concentration and thus the cost of the scrubbing is of no benefit.

Reheating to, say, 175°F ($\Delta T = 50°F$) seems hardly worthwhile at 90 percent SO_2 removal because it only changes ambient

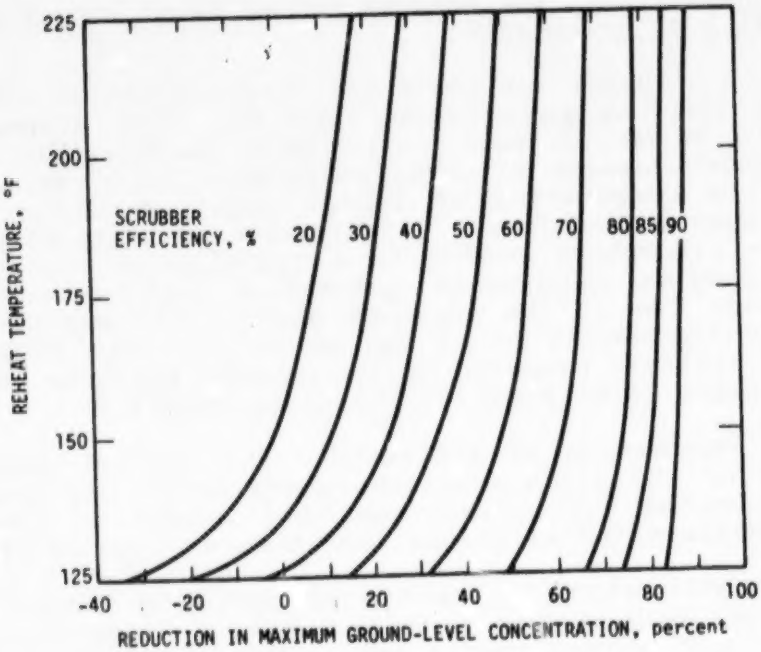


Figure 4.11-10. Effect of reheat temperature (for in-line reheat) on ground-level SO_2 concentration at various scrubber efficiencies.

Base: Maximum ground-level concentration at 300°F without scrubber.

concentration from 83 percent to 88 percent. This is an important consideration with respect to standards requiring 90 percent SO_2 removal efficiency. At 70 percent removal, the effect of the 50°F reheat is more pronounced; reduction in maximum ground-level concentration changes from 48 percent to 65 percent.

It should be noted that the higher water vapor content in the gas offsets to some extent the adverse effects of gas cooling. Since the water vapor has a lower density than other constituents of the gas, it makes the plume more buoyant. The effect is small, however, and has been omitted in developing the curves.

It is concluded that for the high degrees of SO_2 removal (85-95%), reheating is not likely to be economically justified except in marginal situations where the inlet SO_2 to the scrubber is so high that, even with high SO_2 removal, ambient concentration is still close to exceeding the standard.

There are some considerations, however, that may make the situation worse than it appears. If there is no reheat, then the gas leaving the stack can already have a load of mist, in which case evaporation of the droplets as the plume becomes mixed with air can cool the plume and further reduce its buoyancy. A high degree of mist elimination should be achieved if no reheat is used. Moreover, very little NO_x (probably less than 15 percent) is removed in SO_2 scrubbing. Thus NO_x ambient concentration will be greatly increased unless the gas is reheated.

4.11.7 Analysis of Bypass Reheat

This section analyzes bypass reheat to examine its applicability from the standpoint of the emission limitations for sulfur dioxide. Bypass reheat offers the advantages of low capital investment and simple operation. The maximum degree of reheat that can be obtained, however, is limited by the constraints of pollutant emission standards. As mentioned earlier, a regulation requiring 90 percent SO_2 removal efficiency would completely rule out the bypass reheat option. The limitation of sulfur emission to meet the emission standard for sulfur dioxide of 1.2 lb/million Btu can be written as:

$$X = 1 - \frac{1}{E} + \frac{1.2}{2WSE} \qquad \text{(Eq. 4.11-11)}$$

where,

W = amount of fuel required to generate one million Btu/lb

S = weight fraction of sulfur in the fuel

X = fraction of bypass flue gas stream

E = fractional sulfur removal efficiency of the wet scrubbing system

For details of the heat balance around the reheat system, refer to the report Stack Gas Reheat for Wet Flue Gas Desulfurization Systems, prepared by the Battelle Columbus Laboratories for EPRI.[1]

4.11.8 No Reheat

As mentioned previously, stack gas reheat is not required by law. Some power plants have selected, at least temporarily, a "no-reheat" design and accepted the possible consequences--condensation in the ID fan and the stack.

Wash water can be sprayed periodically on the ID fan blades to prevent solid deposits, and a wet stack can be installed to protect the stack from acid attack.

Some advocate "no-reheat" by utilizing a "slow" stack (gas velocity of 30 ft/s) versus a conventional stack (gas velocity of 90 ft/s). The slow stack allows mist droplets (acid rain) to settle out in the stack bottom. This requires special duct and stack material and handling equipment. It also required larger stacks, but these increase opacity problems.

Another alternative for prevention of ground concentration of pollutants is to build a taller stack. A tall stack may be more economical than reheating, even though it involves a high capital cost. There is, by comparison, no energy cost. Under certain circumstances, however, a stack of the required height might not achieve the objective of dispersion for a particular location. Meteorological modeling is a useful tool for determining the validity of such an alternative, but most dispersion models have not been developed for wet plumes.

To limit corrosion in no-reheat operation, one may either select materials that are inherently resistant to corrosion, or use coatings to cover corrodible materials. Discussion of this is included elsewhere in this book. If the purpose of reheat is to protect a downstream fan, an obvious alternative is to place a fan upstream from the scrubber. This is only feasible with an upstream collector or ESP to remove abrasive particulate. Most installations with wet stack operation have stack lining problems. The lining usually blisters and eventually comes off. Once this happens, stack corrosion begins.

As discussed in the chapter on mist elimination, an efficient mist eliminator can reduce the reheat energy requirement or offer no-reheat operation in some cases. It is also obvious that the formation of large particles in the atmosphere by agglomeration and growth is highly unlikely in the absence of large drops. Such formation should not contribute significantly either to stack icing or to rain. Stack icing is the ice that forms on top of the stack under freezing conditions.

4.11.9 Acid Condensation and Reheat

One of the factors that limits boiler efficiency is the effect of corrosion on heat recovery hardware as the temperature of the exit flue gas approaches the critical region of 275° to 300°F. Heat recovery by cooling in a typical power plant requires corrosion-resistant materials, the cost of which cannot be justified.

While most of the sulfur is converted to sulfur dioxide during combustion, a portion of it reacts to form sulfur trioxide (SO_3). Within the scrubber, these acid gases react to form sulfurous and sulfuric acids, some of which are removed in the scrubber. Beyond the scrubber outlet, water vapor continues to condense and reacts with residual SO_2 to form sulfurous acid.

Sulfur trioxide has a far more corrosive effect than sulfur dioxide, although in most boilers the ratio of SO_3 to SO_2 is between 0.01 and 0.03. Even this low concentration of SO_3 raises the gas acid dewpoint temperature considerably. Condensation occurs, and corrosive sulfuric acid is formed. Only partial removal of SO_3 occurs in the scrubber. The degree of removal is difficult to measure because of the limited accuracy of SO_3 determination methods at these low levels.

At a typical SO_3 concentration of 6 to 8 ppm in the hot inlet flue gas stream, theoretical acid dewpoints are between 260°F and 275°F. A typical FGD scrubber outlet level ranges between 1 and 5 ppm. The water dewpoint of scrubbed flue gas is typically about 128°F. The presence of as little as 1 ppm of SO_3 in the flue gas creates an acid dewpoint of above 200°F.

In the final analysis, it is not economical to reheat above the acid dewpoint, but only to reheat sufficiently to prevent significant condensation of moisture in the gas. This means drying the gas to an intermediate point between water dewpoint and theoretical acid dewpoint.

4.11.10 Selecting Optimum Sources of Energy for Gas Reheating

As fuel supplies become more scarce and prices continue to rise, it becomes increasingly important to look for economies in reheat designs. In general, four items must be considered in arriving at an optimum design:

(1) Initial costs of the auxiliary steam system components

(2) Operating costs to produce the auxiliary steam

(3) Pressure level of the source

(4) Boiler or turbine limiting factors

(5) Decreases in reheater area as steam pressure increases

It should be remembered that the penalty associated with steam use from the boiler depends on the point in the cycle at which the energy is extracted. If steam is extracted at the highest temperature and pressure available, the cost of that heat will be very high. On the other hand, if steam is extracted at some intermediate point, the cost is lower. In determining the cost of such heat, its value in terms of extracted work as electrical energy must be considered. The boiler and turbine for new installations must be designed with the reheat steam penalty in mind; otherwise there may be a loss of net power generation capability.

4.11.11 Existing Equipment

This section presents the reheat situation of lime scrubbing installations and reheater problems experienced by each. Table 4.11-1 surveys lime scrubbing installations with in-line reheaters. As the table shows, two of three in-line reheat systems are designed for 50°F reheat and tubes of 1 in. diameter; both have soot blowing arrangements.

Table 4.11-2 surveys direct-fired reheat installations. Power plants that do not reheat the gas are Conesville (Columbus and Southern Ohio Electric Company), Green River (Kentucky Utilities), and Cane Run (Louisville Gas & Electric). Problems developing from not reheating the gas have been encountered in equipment downstream from the mist eliminator. These problems will be discussed in the chapter involving that particular equipment.

4.11.11.1 Hawthorn (Kansas City Power and Light)--

The FGD system at Hawthorn was modified from a limestone injection-based system to a lime slurry-based system. The unit became available for service in the lime scrubbing mode on January 1, 1977. No reheater corrosion problems have been reported. Reheater plugging was a problem, particularly in the B module of the scrubber system. This was solved by removing a section of the reheater to facilitate cleaning and maintenance. Currently, it is a normal practice to shut down the scrubber every 3 days for cleaning the mist eliminator and the reheater. Soot blowing is a heavy maintenance item at this installation. The reheat hot water pump is normally started before placing the scrubber in service.

Table 4.11-1. SURVEY OF IN-LINE REHEAT SYSTEM

No.	Power plant	Heating source	Degree of reheat, °F	Tube style	Heat exchanger tube, diameter inches	Number of tube vanes	Soot blowing	Material of construction
1	Colstrip Montana Power	Steam @ 150 psig and 360°F	30	Plate	1.0	NA	NA	Bottom section is Inconel 625, top section is Hastelloy G
2	Hawthorne Kansas City Power and Light	Hot water @ 325°F	50	Finned	1.5	NA	Steam soot blower	Carbon steel
3	Four Corners Arizona Public Service	Steam @ 600 psig and 650°F	50	Finned	1.0	2	Steam blower once a day	Carbon steel

NA - Not available.

Table 4.11-2. SURVEY OF DIRECT-FIRED REHEAT SYSTEM

No.	Power plant	Degree of reheat, °F	Fuel and Combustion				
			Fuel type	Sulfur content, %	Fuel rate	Excess air, %	Gas temperature, °F
1	Phillips Duquesne Power	30	No. 2 fuel oil	0.3	440 gal/h	NA	3000
2	Elrama Duquesne Power	30	No. 2 fuel oil	0.3	440 gal/h	NA	3000
3	Bruce Mansfield Pennsylvania Power	40	No. 2 fuel oil	0.2	NA	NA	NA
4	Paddy's Run Louisville Gas and Electric	40	Natural gas	0	20,000 scfh	6-9	NA

NA = Not available.

4.11.11.2 Four Corners (Arizona Public Service)--

In this horizontal scrubber reheater, the carbon steel tubes developed pinholes. Metallurgical examination revealed that the pinholes, which developed from inside the tube, were caused by stagnant condensate and air that leaked into the reheat system. It is not known when the pinholes developed; however, the system had been idle for a year before testing, and it is likely they occurred during this idle period. This problem was resolved by installation of a nitrogen (N_2) blanket system in the reheater loop to exclude air from inside the tube. The pinholes were brazed so that system testing could continue.

This horizontal scrubber has now been shut down indefinitely. There is no feedback regarding the nitrogen blanket performance.

4.11.11.3 Colstrip (Montana Power)--

In this in-line reheater installation no corrosion problems have been reported. Materials of construction are Inconel 625 and Hastelloy G. Although some loose scale formed on the reheater tubes, it did not cause any operating problems.

4.11.11.4 Phillips Station (Duquesne Light & Power)--

In this direct-fired reheat system, the design value for reheat temperature was not high enough to protect the lined stack. The blower failed because of mechanical problems. Problems occurred with the oil pumps, burners, and temperature control system, and corrosion has been reported in the combustion chamber. No priority has been placed on operating the reheater because of the oil shortages. A new acid-proof stack liner has been installed. The scrubber system is currently operated with a wet stack.

4.11.11.5 Elrama Station (Duquesne Light & Power)--

In this direct-fired reheat system, problems similar to those at the Phillips station have been encountered (see Section 4.11.11.4).

4.11.11.6 Bruce Mansfield (Pennsylvania Power Co.)--

In this direct-fired reheat system, combustion problems have occurred because of the flue gas mixing with the combustion air. This in turn has caused problems in maintaining a flame in the combustion chamber.

Vibration in the reheat system is another problem. All these problems are to be resolved by the equipment supplier, but plans for doing so were not available at the time of this writing.

4.11.11.7 Paddy's Run 6 (Louisville Gas & Electric Co.)--
No problems have been reported in this direct-fired reheat system.

4.11.12 Recommendations

There is a good deal of disagreement over the selection of the appropriate type of reheat system and material of construction. Any one of the following four options is recommended, but each has drawbacks:

(1) An in-line reheat system constructed of carbon steel, which uses finned tubes and hot water.

(2) An in-line reheat system employing steam and a plate-coil-type heat exchanger constructed of Hastelloy. This type can be corrosion-resistant; however, use of Hastelloy raises the capital cost.

(3) An indirect hot-air reheat system constructed of carbon steel. The main drawback of this option is that it involves heating a portion of ambient air and hence has a higher operating cost.

(4) A direct-firing reheat system using oil. Its main drawback is that oil is expensive and in short supply.

Other general recommendations are as follows:

- A soot blower should be installed.
- An efficient mist eliminator should be installed to decrease the load on the reheat system.
- Gas should be heated by 25° to 50°F to prevent downstream water condensation.

REFERENCES

1. Choi, P. S. K., S. A. Bloom, H. S. Rosenberg, and S. T. DiNovo. Stack Gas Reheat for Wet Flue Gas Desulfurization Systems. EPRI Research Project prepared by Battelle Columbus Laboratories. November 1, 1976.

2. National Air Pollution Control Administration. Sulfur Oxide Removal from Power Plant Stack Gas -- Use of Limestone in the Wet Scrubbing Process. Conceptual Design and Cost Study Series, Study No. 2. Prepared for Tennessee Valley Authority. 1969.

BIBLIOGRAPHY

Hollinden, G. A., et al. Reheat Study and the Corrosion-Erosion Tests at TVA's Colbert Pilot Plant. EPRI Report RP537-1. September 1978.

PEDCo Environmental, Inc. EPA Utility FGD Survey. Prepared bimonthly under Contract No. 68-01-4147.

CONTENTS

4.12 CORROSION

		Page
4.12.1	Introduction	4.12-1
4.12.2	Types of Corrosion	4.12-1
4.12.3	Corrosion Design and Material Selection	4.12-2
4.12.4	Coatings	4.12-4
4.12.5	Construction Techniques	4.12-8
4.12.6	Process Operation	4.12-8
4.12.7	Reheaters	4.12-8
4.12.8	Stacks	4.12-15
4.12.9	Examples of Existing Plants	4.12-16
4.12.9.1	Green River (Kentucky Utilities Company)	4.12-16
4.12.9.2	Cane Run Station 4 (Louisville Gas and Electric Company)	4.12-16
4.12.9.3	Conesville No. 5 (Columbus and Southern Ohio Electric Co.)	4.12-16
4.12.9.4	Phillips and Elrama, Boiler No. 2 and One Other (Duquesne Light Company)	4.12-17
4.12.9.5	Hawthorn Nos. 3 and 4 (Kansas City Power and Light Company)	4.12-17
4.12.9.6	Bruce Mansfield Nos. 1 and 2 (Pennsylvania Power Company)	4.12-17
References		4.12-18
Bibliography		4.12-20
Glossary		4.12-21

4.12 CORROSION

4.12.1 Introduction

Consideration of the corrosion phenomenon is important in the design and construction of any plant and is particularly so in the case of flue gas desulfurization (FGD) systems. Many FGD systems have experienced severe corrosion despite ongoing efforts by the utilities to find corrosion-resistant materials. The materials of construction for the scrubber were discussed in Section 4.6.3. This section discusses some of the more important factors concerning corrosion of stacks and reheaters as well as the plant experience of operational lime FGD systems.

4.12.2 Types of Corrosion

There are various specific types of corrosion. General corrosion, pitting, crevice corrosion, intergranular corrosion, stress corrosion cracking, and erosion-corrosion are the types of corrosion most commonly found in FGD systems and hence will be given special consideration. Other types of corrosion will also be discussed.

General corrosion is the uniform dissolution of an entire metallic surface.[1] It is the best understood of all the corrosion processes. The required conditions are usually not very specific, occurring over wide variations in solution composition, pH, etc.[2] General corrosion is a controllable problem in that the lifetime of the equipment can be accurately predicted by laboratory tests or theoretical calculations.

Pitting is intense attack at certain locations on the metallic surface because of local film breakdown.[3,4] Pits or holes form and usually result in rapid perforation of the material.

Crevice corrosion is in many ways similar to pitting erosion: intense attack occurs within preexisting crevices as a result of the formation of concentration cells, etc.[5]

Intergranular corrosion is localized corrosion occuring at, or immediately adjacent to, the grain boundary. Chemical heterogeneities, such as a segregate or precipitate at the grain boundary, cause a local galvanic cell to be established, and the grain boundary dissolves.

Stress corrosion cracking encompasses a complex spectrum of failure mechanisms.[6,7] The area is still one of intense research. Essentially, failure is caused by the combination of a specific environment, a tensile stress of sufficient magnitude and, usually, a specific metallurgical requirement in terms of the composition and structure of the alloy. Alloys subject to stress corrosion cracking are not normally considered to be markedly susceptible to general corrosion in the environment.[8]

Erosion-corrosion is the effect of the joint action of mechanical forces and a corrosive environment. Debris or suspended solids impinge upon a susceptible surface, destroy the protective surface film, and thereby expose the alloy to the corrosive agent. Cavitation and subsequent bubble collapse have the same effect.[9]

Other corrosion processes of interest include corrosion fatigue and galvanic corrosion. In corrosion fatigue, the fatigue life of the structure is greatly reduced by the effect of the corrosive environment.[10] The process is not well understood, but in several ways resembles both stress corrosion cracking and erosion-corrosion. Galvanic corrosion occurs when two dissimilar metals are joined in a conducting solution. Severe corrosion of the less noble metal occurs at the metal-metal junction. Many common forms of joining (welding, brazing, soldering, bolting) provide junctions at which galvanic corrosion can develop; this should be considered in the design stage. Galvanic corrosion on a microscopic scale can also occur between the constituents of multiphase alloys.

4.12.3 Corrosion Design and Material Selection

A structural design that will minimize or allow for erosion is of the highest importance. The science of corrosion design is closely related to economics and process safety.

For a given piece of equipment and a given set of operating conditions there is often a wide choice of possible materials. Selection of a low-cost material when general corrosion prevails in the scrubber environment can be the most economical option in that corrosion will occur at a predictable rate and the equipment can be periodically replaced during planned maintenance periods; however, the expense of frequent maintenance or extensive downtimes of a particular section of a plant (and the possible need for backup equipment) can be limiting factors. Use of more expensive corrosion-resistant materials is another alternative; however, these materials must be selected carefully to ensure, first, that they will have a lifetime that will justify the higher cost and, second, that they will not be prone to the more severe types of corrosion such as pitting corrosion and stress corrosion cracking. The corrosion rates for these types of failure are difficult to predict, and the results can be catastrophic if corrective action is not taken. Nevertheless, it is possible to derive theoretical relationships that enable alloys susceptible to stress corrosion cracking in a given environment to be used with comparative safety. In recent years it has been realized that real structures inevitably contain flaws. That is, actual cracks already exist and the engineer has therefore to develop criteria to ascertain whether, and at what applied load (σ_{app}), any of these cracks will propagate to the point of failure.

Fracture mechanics is the analysis of the stresses in the neighborhood of preexisting cracks of specified geometry.[11] The effective stress intensity, K, close to the root of a given crack is directly proportional to σ the crack length. Values for K_{ISCC}* can be obtained by experiment, and hence loading conditions can be established for each section of the plant so that the stress corrosion cracks do not propagate. Current developments in the field of fracture mechanics allow plastic deformation to be considered.[12]

Other alternatives in material selection are to isolate the structural alloy from the corrosive environment by a barrier or to design corrosion control systems. These include the addition of inhibitors in circulating liquids or in paint coatings, or the superimposition of anodic or cathodic protection.[13] The concept of isolating the structural alloy from the environment is simple, but it has proved difficult to achieve. It is discussed more fully in Section 4.12.4.

Correct materials selection and corrosion design must avoid junctions between dissimilar metals that would promote galvanic corrosion. One way of doing this is to use washers to insulate bolts from a structure. Other possibilites include painting the more noble constituent of a couple to give a large anode area and a very small cathode area, which will ensure a very slow corrosion rate. Some problems arise here, however. It is not always possible to predict from the electrochemical table which metals will be anodes and which will be cathodes when joined, or what the cell voltage will be. For example, if a highly reactive metal is covered by a protective oxide film, its ions cannot easily enter into solution, even though the metal is readily ionizable. Galvanic corrosion problems can be encountered in welded structures. This is discussed more fully in Section 4.12.5 (Construction Practices).

Correct material selection requires an understanding of corrosion, a careful evaluation of process conditions in the proposed section of plant, an extensive literature survey, and practical research. Much can be learned from past failures. Reference to standard works would also prove beneficial.[14]

---

* K_{ISCC} = K for the most severe stress condition (plane strain) in an environment promoting stress corrosion cracking.

Proper structural design is equally important. Crevices, high flow areas, and areas of evaporation are just a few examples of sites that promote corrosion. Debris collecting in a crevice can give a low-oxygen concentration, and possibly set up an anode-cathode system; debris can similarly collect at the flashing around welds. High flow areas may cause the breakdown of protective oxide fibers. Areas of evaporation can lead to salt concentration and the possibility of increased corrosion.

External environmental conditions have their effect, too. For example, marine environments have a high concentration of chlorides. This can be of importance in areas where dew or rainwater collects and possibly evaporates, which can lead to chloride concentration and subsequent corrosion problems.

Incorporating additional components in an FGD system can be helpful in preventing corrosion. For example, the inclusion of reheaters immediately after the scrubbing module will reduce corrosion problems in stacks and achieve plume enhancement and pollutant dispersion. The reheaters heat the gas and reduce the probability of condensation on the stack wall. It is necessary, however, to optimize conditions to obtain a balance between the occurrence of condensation and the maximum service temperature of the stack material. Correct materials selection and design are required to prevent severe corrosion of the reheaters. This will be discussed further in Section 4.12.7.

4.12.4 Coatings

Coatings are of particular interest because they are used extensively in scrubber systems. This section will discuss paints, liners, bricks, and their application. The object of a coating is to prevent the access of corrosive liquors to the bare metal surface. In practice, however, all coatings are somewhat permeable and a dual objective of some is to treat any permeating liquor and thereby prevent corrosion.

Paints are suitable in some situations. Although they are porous, they decrease the available surface area. Inhibitors such as natural oils, lead, chromate, phosphates, and silicates are often incorporated into the paint. Paints can be used either as a final treatment or as an intermediate treatment to prevent corrosion during construction when field application of a liner or brick structure is intended.[15,16]

Glass linings have been used on heat exchangers in Russia to protect steel in chloride environments.[17] Although the heat transfer coefficient of a glass lining is initially 10 percent lower than that of carbon steel, it remains constant, whereas the steel surface oxide film becomes thicker and its heat transfer coefficient is progressively lowered.

Linings of concrete, e.g., Precrete, have been employed in FGD stacks with varying success (see Section 4.12.9).

Various brick linings are also used to protect stack structures in FGD units and also in venturi throats. They have advantages in being able to withstand high temperatures and corrosion, but those currently used have the disadvantage that acid seeps through the brick mortar joints and leads to corrosion of the supporting structural steel.

Irrespective of the actual coating specified for the stacks, an important consideration is its correct application to the structural steel so as to prevent subsequent delamination. This can be accomplished by the employment of highly skilled operators and the use of rigorous inspection techniques. Correct preparation of the surface is also important, and the following general guidelines are provided.

Prior to application of a coating:

(1) All surfaces should be cleaned in accordance with Steel Structures Painting Council (SSPC) Spec. SP 6-63.[18]

(2) All air sources, including blasting, cleaning, and spraying should be free of oil and water. Effective traps and filters should be installed and frequently inspected.

(3) Prior to any required abrasive cleaning, surfaces should be precleaned according to SSPC Spec. SP 1-63 to remove grease, oil, and loosely adhering deposits.

(4) Cleaning should not be performed if any of the following conditions are suspected or evident.

    a. Moisture is present on the surface.
    b. Moisture condensation is imminent.
    c. The abrasive is wet.
    d. The blasting operation interferes with painting.
    e. The cleaning equipment is not in good operating condition.

(5) Surfaces should be blasted in conformance with the following requirements.

    a. Blasting equipment should be in good condition to prevent any moisture, oil, or other foreign matter from depositing on the surface during blasting in accordance with SSPC Spec. SP 6-63. Pressure should be 100 psi as measured at the nozzle.

b. A depth profile between 2 and 4 mils should be attained.

(6) The surface should be cleaned by a vacuum cleaner and dust blown off with compressed air (free from oil and water) after sandblasting. Any oil, grease, or other detrimental materials adhering to the surface after blasting should be removed by solvent washing and reblasting.

(7) The blast-cleaned surfaces should be coated within 4 to 6 hours of blasting and before any rusting occurs. If rusting does occur, the surfaces should be reblasted to the degree specified.

(8) When a wet or water vapor sandblasting method of surface preparation is required in hazardous areas, the procedure written by the SSPC should be followed.

(9) Machined parts, bearings, and motors must be adequately protected during sandblasting to prevent sand from endangering their operation. If these pieces of equipment cannot be protected, they should be removed.

Specification SP 6-23 of SSPC is a commercial blast cleaning process stating the maximum amount of residue permitted on a steel surface before application of a coating. Near-white metal blast cleaning (SSPC Spec. SP 10-63T) and white metal blast cleaning (SSPC Spec. SP 5-63) result in cleaner surface finishes than produced by commercial blast cleaning. The following are definitions supplied by the SSPC for the three types of sandblasting:

- Commercial Blast-Cleaned Surface Finish
  All oil, grease, dirt, rust, scale, and foreign matter have been completely removed from the surface and all rust, mill scale, and old paint have been completely removed except for slight shadows, streaks, or discolorations caused by rust stain, mill scale, oxides, or slight, light residues of paint or coating that may remain; if the surface is pitted, light residues of rust or paint may be found in the bottom of pits; at least two-thirds of each square inch of surface area should be free of all visible residues and the remainder limited to the light discoloration, slight staining, or light residues mentioned above.

- Near-White Blast-Cleaned Surface Finish
  All oil, grease, dirt, mill scale, rust, corrosion products, oxides, paint, or other foreign matter have been completely removed from the surface except for very light shadows, very slight streaks, or slight

discolorations caused by rust, stain, mill scale, oxides, or slight, light residues of paint or coating that may remain. At least 95 percent of each square inch of surface area should be free of all visible residues, and the remainder limited to the light discoloration mentioned above.

- White Metal Blast-Cleaned Surface Finish
  A surface with a gray-white, uniform, metallic color, slightly roughened to form a suitable anchor pattern for coatings. The surface, when viewed without magnification, should be free of all oil, grease, dirt, visible mill scale, rust, corrosion products, oxides, paint, or any other foreign matter. The color of the clean surface may be affected by the particular abrasive medium used.

The following is a list of materials typically used when pressure blasting for a specified anchor pattern. The profile depth is an approximation and not a minimum or maximum depth obtainable.

2-mil Profile

16/35-mesh silica sand
G-40 steel grit
S-230 steel shot
36-mesh garnet
36 Grit aluminum oxide
Clemtex No. 3
Black Beauty BB-50 or BB-2040

2.5-mil Profile

8/35-mesh silica sand
G-40 steel grit
S-280 steel shot
16-mesh garnet
24 Grit aluminum oxide
Clemtex No. 2
Black Beauty BB-400

3- to 4-mil Profile

8/20-mesh silica sand
G-25 steel grit
S-330 or 390 Steel shot
16-mesh garnet
16 Grit aluminum oxide
Clemtex No. 2
Black Beauty BB-40 or BB-25

Shot-grit blasting has additional advantages in that it gives a deformed surface layer that resists stress corrosion cracking.[19]

4.12.5 Construction Techniques

From some points of view, the optimum design of any structure calls for its fabrication from a single sheet of metal, which permits a smooth, continuous surface. Welds on overlapping pieces of metal create stagnant areas where corrosion attack intensifies. Since it is usually impossible to design a structure with no welds, care should be taken in constructing the welds. Crevices should be avoided and the possibility of galvanic corrosion considered. Figures 4.12-1 through 4.12-5 show some recommendations for welding techniques. Generally, the filler metal should be more noble than the structural metal in order to prevent galvanic corrosion.

4.12.6 Process Operation

Process operation is another important consideration in the prevention of corrosion. Monitoring flow rates, temperatures, pH, etc., will indicate when process conditions are deviating from the design conditions. Chemical additions to restore pH or bypasses to protect delicate parts of the process are suggested. For example, at Green River, where the FGD system has been retrofitted, the existing stack can be used for hot flue gases when the FGD system is not operating. This protects the temperature-sensitive walls of the FGD stack.

4.12.7 Reheaters

To date, only limited data have been published on reheaters and corrosion. The work of Zotor et al. has already been discussed in Section 4.12.4.[17] The Tennessee Valley Authority (TVA) has also recently completed a study.[20]

In the TVA study, the main material problems arose from mud-like carryover from the mist eliminator. The carryover was deposited on the reheater tubes, the moisture evaporated, and concentrations of chlorides and sulfur oxides caused pitting corrosion. The use of air blowers should prevent this deposit buildup and hence reduce corrosion. Problems were also experienced because of shutdowns. When the temperature of the reheaters dropped below the acid dewpoint, acid condensed on the tubes and caused severe corrosion. Condensation on the tubes could be prevented by maintaining steam flow to the reheaters, even when the scrubber is not operating.

During the TVA program, the materials listed in Table 4.12-1 were studied. The report notes that although these results seem, on the whole, to be satisfactory, many can be susceptible to stress corrosion cracking.

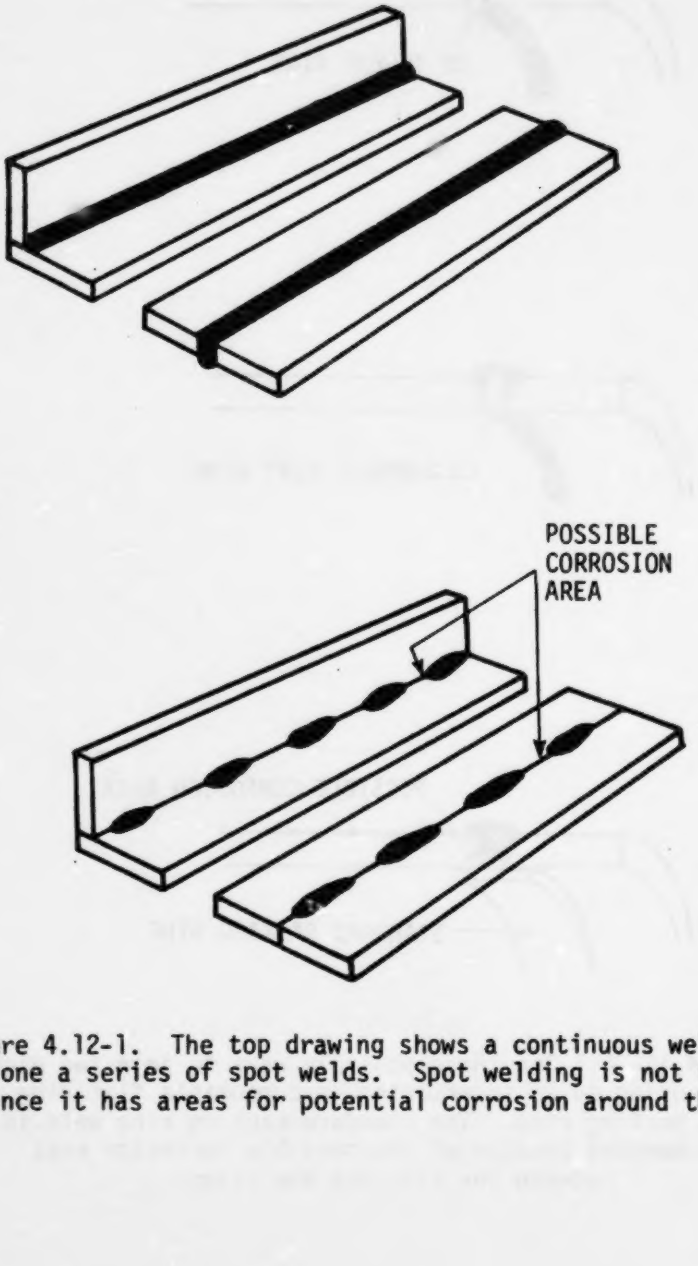

POSSIBLE
CORROSION
AREA

Figure 4.12-1. The top drawing shows a continuous weld and the lower one a series of spot welds. Spot welding is not recommended since it has areas for potential corrosion around the joint.

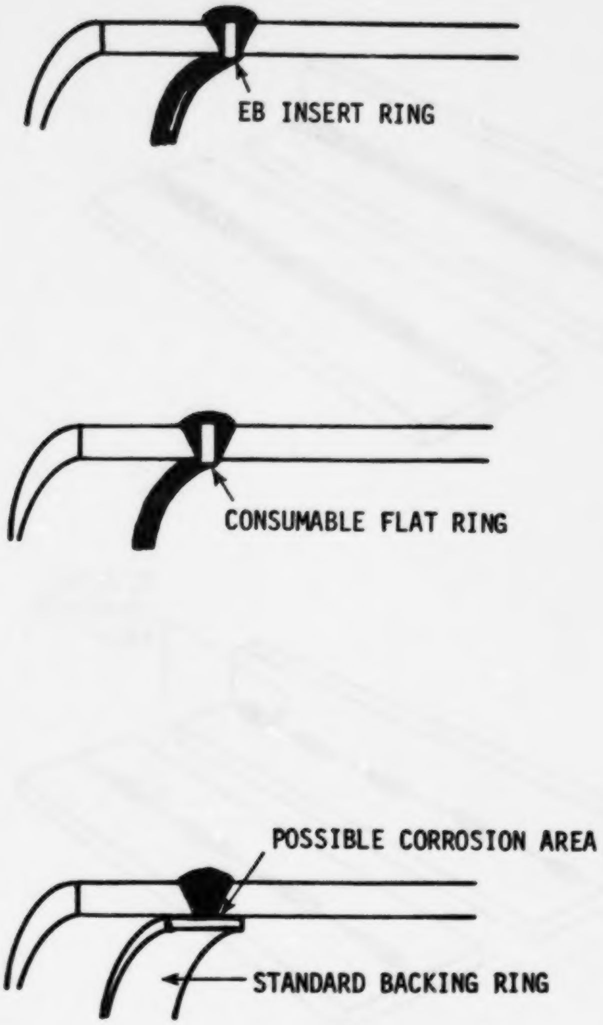
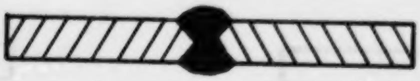
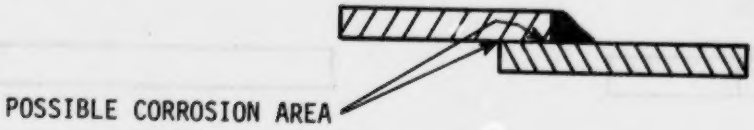

EB INSERT RING
CONSUMABLE FLAT RING
POSSIBLE CORROSION AREA
STANDARD BACKING RING

Figure 4.12- 2. The three possible ways to join two pieces of pipe by using an EB insert ring, a consumable flat ring, or a standard backing ring. The standard backing ring weld is not recommended because of the possible corrosion area between the ring and the pipes.

DOUBLE BUTT WELD



LAP WELD, SINGLE FILLET


POSSIBLE CORROSION AREA

LAP WELD, DOUBLE FILLET

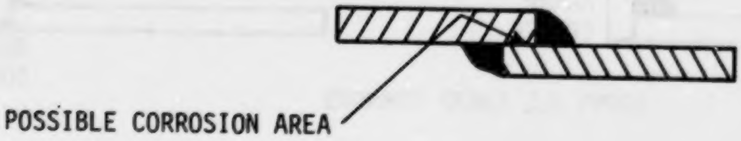

POSSIBLE CORROSION AREA

Figure 4.12-3. Examples of a double butt weld, single fillet lap weld, and double fillet lap weld. The double butt weld is recommended because the joint is filled.

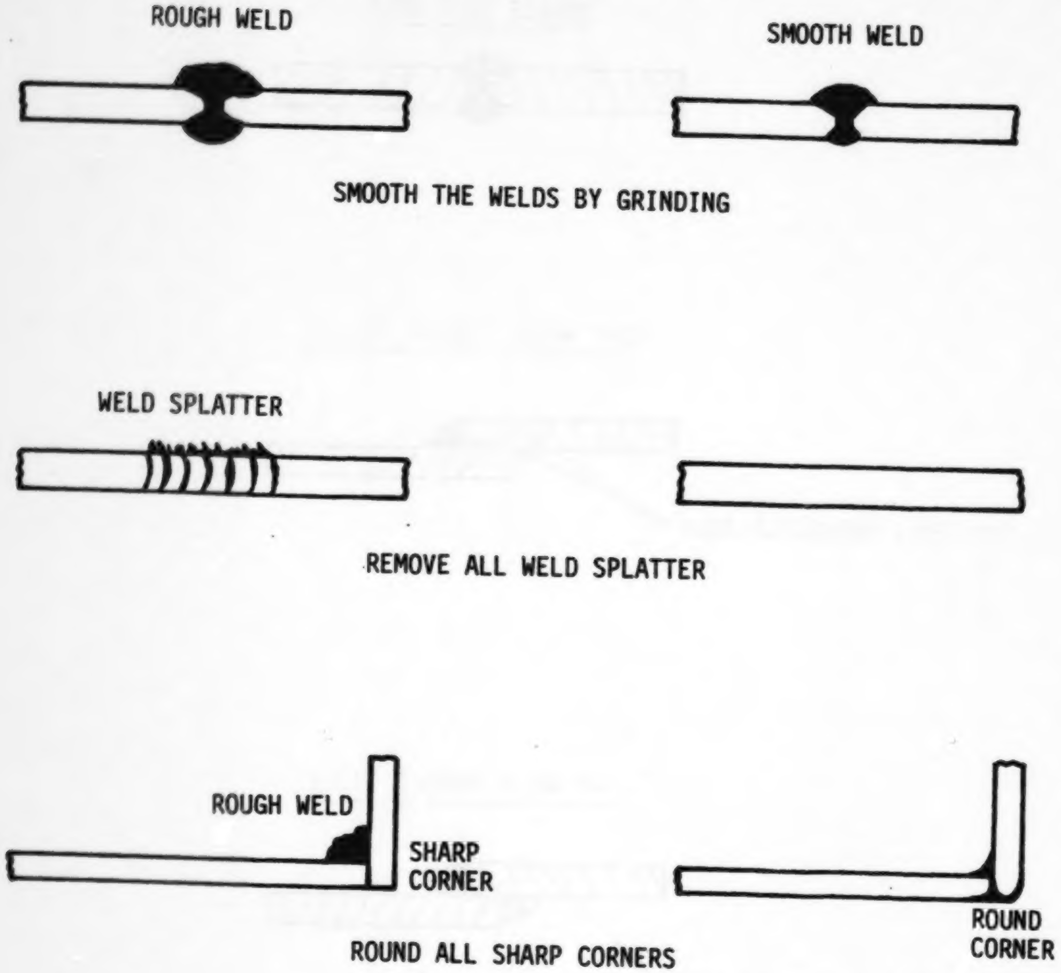

ROUGH WELD
SMOOTH WELD
SMOOTH THE WELDS BY GRINDING
WELD SPLATTER
REMOVE ALL WELD SPLATTER
ROUGH WELD
SHARP CORNER
ROUND CORNER
ROUND ALL SHARP CORNERS

Figure 4.12-4. Examples of good and bad finishing techniques for welds.

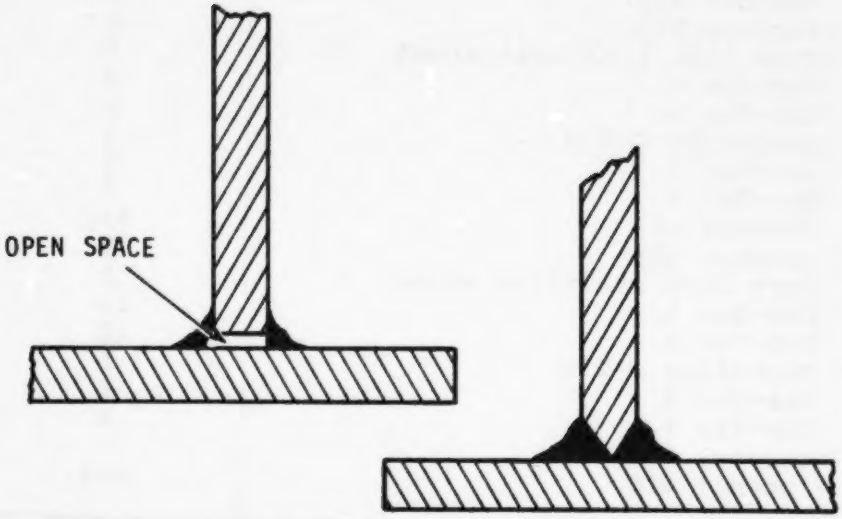


Figure 4.12-5. Always make a complete full weld.

Table 4.12-1. CORROSION OF REHEATER TUBES FROM COLBERT PILOT PLANT AFTER 3800 HOURS[19]

Tube No.[a]	Alloy	Corrosion rate, mils/yr
1	Inconel 625	1
2	Inconel 625	2
3	Inconel 625	1
4	Incoloy 825	b
5	Type 316L stainless steel	b
6	Cor-Ten A	8
7	Cor-Ten A	9
8	Hastelloy C-276	1
9	Cor-Ten A	8
10	Cor-Ten A	9
11	Inconel 625	Neg.
12	Incoloy 625	b
13	Type 316L stainless steel	b
14	Cor-Ten A	13
15	Cor-Ten A	12
16	Hastelloy C-276	b
17	Cor-Ten A	8
18	Cor-Ten A	8
19	Inconel 625	1
20	Inconel 625	Neg.

[a] Tubes are numbered from left to right, facing the incoming gas.

[b] Pits were visible, but they were too small to measure depth.

Neg. - Negligible

Boiler stacks are massive, expensive structures that are difficult to maintain or replace and are subject to corrosion. Before the introduction of FGD systems, and where such controls are unnecessary, stainless and mild steels have proved to be satisfactory stack construction materials. The use of Cor-Ten has also been suggested. The satisfactory performance record was due to the fact that the exhaust gases were dry and hot (above the acid dewpoint) and did not condense on the stack walls, although problems can be experienced from condensation at the top of the stack.

The use of wet FGD systems, which saturate the flue gas with moisture, necessitates the use of more sophisticated materials for the stack and the reheaters. In a few cases, very expensive, corrosion-resistant alloys have been used, but more commonly bricks are employed as stack liners. As previously discussed in Section 4.12.4, seepage is a problem with brick linings. Some utilities are attempting to solve this by using a positive pressure between the steel structure and the brickwork. Other coatings have been used in stacks to prevent corrosion. With or without reheat, most of the coatings have performed satisfactorily under normal operating conditions; however, when the FGD system is bypassed, the exhaust gases are considerably hotter (in excess of 284°F) and may damage the lining. The stack shell is exposed and is then susceptible to corrosion.

Precrete has been used at some locations with good results. It is not corrosion-resistant, but it fails at a predictable rate. The utility companies have been able to apply a thick layer of Precrete to stack shells at a reasonable cost. Precrete may not be applicable for new large boilers, which have limited downtime for relining.

4.12.8 Stacks

Boiler stacks are massive, expensive structures that are difficult to maintain or replace and subject to corrosion. Before the introduction of FGD systems, and where such controls are unnecessary, stainless and mild steels have proved to be satisfactory stack construction materials. The use of Cor-Ten has also been suggested. The satisfactory performance record was due to the fact that the exhaust gases were dry and hot (above the acid dewpoint) and did not condense on the stack walls, although problems can be experienced from condensation at the top of the stack.

The use of wet FGD systems, which saturate the flue gas with moisture, necessitates the use of more sophisticated materials of construction for the stack and/or the use of the reheaters. In a few cases, very expensive, corrosion-resistant alloys have been used, but more commonly bricks are employed as stack liners. As previously discussed in Section 4.12.4, seepage is a problem with brick linings. Some utilities are attempting to solve this problem by using a positive pressure between the steel structure and the brickwork (see Section 4.12.9.4). Other coatings have been used in stacks to prevent corrosion. With or without reheat, most of the coatings have performed satisfactorily under normal operating conditions; however, when the FGD system is bypassed, the exhaust gases are considerably hotter (in excess of 284°F [140°C]) and may damage the lining. The stack shell is exposed and is then susceptible to corrosion.

Precrete has been used at some locations with good results. It is not corrosion-resistant but it fails at a predictable rate. Utility companies have been able to apply a thick layer of Precrete to stack shells at a reasonable cost. However, Precrete may not be applicable for new large boilers, which have limited downtime for relining.

4.12.9 Examples of Existing Plants

This section details examples of materials problems in existing plants.

4.12.9.1 Green River (Kentucky Utilities Company)--

The stack lining was initially Carboline, which had to be replaced because of excessive flaking. The stack was relined with Precrete in 1977 to withstand design capabilities of a pH 5 to 9 and up to 300°F.

4.12.9.2 Cane Run Station 4 (Louisville Gas and Electric Company)--

The ductwork at the Cane Run plant was originally made of mild steel and coated with Carboline. Bubbles formed in the Carboline coating, but it did not fail. This coating was removed in May 1977 and replaced with Plasite 4005. The performance of the Plasite 4005 has not been reported.

The 250-ft stack for Boiler 4 is made of concrete and lined with acid brick. The brick was coated with a Carboline layer. The Carboline coating and the brick began to fail, and in May 1977 they were removed. A 2-in. layer of Precrete was installed in their place. The stack was inspected after a year of operation; the Precrete was holding up very well.

4.12.9.3 Conesville No. 5 (Columbus and Southern Ohio Electric Co.)--

The ductwork of the FGD system on Boiler 5 is made of Cor-Ten steel and coated with Saurereisen 54 Gunite. No adverse reports have been received regarding its performance. The outer shell of the 800-ft stack is concrete. The shell was originally lined with a Cor-Ten steel flue, which was coated with a Ceilcote liner. This liner failed because of continual bypass of the scrubbing system. When this occurred, flue gases entering the stack were too hot for the Ceilcote liner to handle. Once the liner failed, the Cor-Ten flue was exposed to the flue gases and began to corrode. It was replaced in December 1977 with a fireclay brick liner using Saurereisen 65 mortar.

4.12.9.4 Phillips and Elrama, Boiler No. 2 and One Other[20] (Duquesne Light Company)--

The lime FGD systems at these plants are identical. The original ductwork was made of 316L stainless steel. It corroded and was replaced with a mild steel shell coated with Ceilcote 103. There have been no subsequent problems.

Each stack consists of a concrete shell with an acid brick liner. The mortar used is Saurereisen 65. Sulfuric acid seeping through the brick caused problems. The brick liner was repaired and a positive pressure maintained in the space between the concrete and brick. It is hoped this measure will prevent a recurrence of sulfuric acid seepage.

4.12.9.5 Hawthorn Nos. 3 and 4 (Kansas City Power and Light Company)--

The ductwork and the stack at the Hawthorn plant had no corrosion problems. The ductwork was built of carbon steel and lined with a 2-in. layer of Gunite. The stack was built of steel and lined with Gunite. These materials were installed in 1972 when the FGD systems went into service.

4.12.9.6 Bruce Mansfield Nos. 1 and 2 (Pennsylvania Power Company)--

Unit 1 has two carbon steel stacks, which were originally lined with polyester flakeglass. In May 1977, the polyester flakeglass lining failed and the flue gas caused extensive damage to the carbon steel structure. After a 10-week maintenance outage, the stacks were repaired one at a time while the unit was operating at approximately half load. The unit came back to full load by January 1978. A very similar polyester flakeglass lining has held up reasonably well in the scrubber and absorber vessels and the ductwork. Plant personnel have tested patches of various linings in one stack of Unit No. 2.

REFERENCES

1. Shrier, L. L. Corrosion. 2nd ed. Newnes Butterworth, London, Boston, Sydney, 1976.
2. Pourbaix, M. Atlas of Electrochemical Equilibria in Aqueous Solutions. Pergamon Press, London, 1966.
3. Hoar, T. P. et al. Corro. Sci., 5, 279, 1965.
4. Hoar, T. P. Corros. Sci., 7, 341, 1967.
5. Fontana, M. G., and N. D. Greene. Corrosion Engineering. McGraw-Hill, 1967. pp. 28-115.
6. Parkins, R. N. Ref. 1, pp. 8.03-8.35.
7. Fundamental Aspects of Stress Corrosion Cracking. N.A.C.E., Katy, Texas, 1969.
8. Tems, R. D. Thesis, University of Newcastle Upon Tyne, 1978.
9. West, J. M. Electrodeposition and Corrosion Processes, Van Nostrand Reinhold, 1971.
10. Handbook of Fatigue Testing. ASTM, 1974.
11. Ref. 9, p. 133.
12. Chell, G. G. CEGB Research, Jan. 1978, pp. 36-44. (CEGB, Leatherhead, Surrey, England).
13. Lui, A. W., and G. R. Hoey. Materials Performance 15, 13-16, 1976.
14. Schweitzer, P. A. Corrosion Resistance Tables. Marcel Dekker, Inc., 270 Madison Ave. New York, New York 1976.
15. Brooks, M. E. Bull Inst. Cor. Sci. Tech., No. 4, 2-9, 1977.

16. Lapasin, R. et al. Brit. Cor. J., 12, 92-102, 1977.

17. Zotov, A. G. et al. Teploenergetika, 58-60, May 1976.

18. Kaplan, N., and J. C. Herlihy. IERL-Research Triangle Park, North Carolina.

19. Brown, A., and R. Wilkins. Eurocor '77, pp. 563-570.

20. Hollinden, G. A. et al. Reheat Study and the Corrosion-erosion Test at TVA's Colbert Pilot Plant. Published by EPRI (EPRI RP 537-1). Palo Alto, California, September 1978.

BIBLIOGRAPHY

NACE Surface Preparation Handbook. NACE, Katy, Texas.

Staehle, R.W. et. al., eds. Stress Corrosion Cracking and Hydrogar Embrittlement of Iron Base Alloys (Firming France 1973). NACE (No. 51102).

Resolving Corrosion Problems in Air Pollution Control Equipment. NACE 1976 (No. 52100).

Surface Preparation Specifications. Steel Structures Painting Council, Pittsburgh. pp. 3, 31-38, 47-50, 1963.

Heil Process Equipment Company. Surface Preparation.

Dudick Corrosion Proof, Inc. Application Guide: Surface Preparation.

Corrosioneering, Inc. Resista-Flake 1200 Series. Thermosetting Lining Systems Application Guide RFA 1200.

Wyatt, C.H. Coatings--A Chain Link Fence. In: Corrosion Problems in Air Pollution Control Equipment Symposium, Atlanta, Georgia, 1978.

Singleton, W.T., Jr. Protective Coatings Formulated from Vinyl Ester Resins for the Air Pollution Industry. In: Corrosion Problems in Air Pollution Control Equipment Symposium, Atlanta, Georgia, 1978.

Landrum, R.J. Designing for Corrosion Resistance of Air Pollution Control Equipment. In: Corrosion Problems in Air Pollution Control Equipment Symposium, Atlanta, Georgia, 1978.

Graver, D.L. Forms of Corrosion. In: Corrosion Problems in Air Pollution Control Equipment Symposium, Atlanta, Georgia, 1978.

GLOSSARY

Anchor pattern - The surface morphology that ensures adhesion of a coating to the surface.

Concentration cell - An area in which dissolved ion concentrations differ from the bulk environment; it can include increased concentrations of dissolved species or decreased concentrations of a dissolved species; the pH may be affected; these differences can occur in crevices, cracks, pits, or restricted flow areas; the term "occluded cell" is a concentrations cell in which the oxygen concentration is reduced.

Film - A barrier between the metal and the solution formed by the reaction between the same, and usually consisting of a metal oxide; this surface film may be protective and prevent further general corrosion (e.g., the film on stainless steels) or it may offer no protection at all (e.g., a rust film).

High flow areas - Here, an area in which high flow rates may impinge on the surface film, damaging it, and exposing the metal to further corrosive action.

Plastic deformation - Damage to a material such that it cannot, of its own accord, regain its original shape and characteristics.

Precipitate - One or more of the constituents of an alloy that settle out as a distinct phase in the matrix; this phase can be dispersed throughout the matrix (e.g., graphite in grey cast iron) or localized to particular areas (e.g., chromium carbide precipitated at the grain boundary when stainless steels suffer from weld decay).

Segregate - Similar to precipitate, except that the constituents do not settle out as a separate phase, but merely become concentrated within certain areas of the matrix.

Shot-grit blasting - Blasting using a mixture of 80 percent shot and 20 percent grit; the grit gives a better anchor pattern whereas the shot has other beneficial effects.

CONTENTS

4.13 INSTRUMENTATION

Page

4.13.1 Introduction 4.13-1

4.13.2 pH Control 4.13-1

- 4.13.2.1 Reference Electrodes 4.13-1
- 4.13.2.2 Electrode Cleaning Devices 4.13-2
- 4.13.2.3 Electrode Installation 4.13-2
- 4.13.2.4 pH Controller 4.13-4
- 4.13.2.5 Performance History 4.13-5

4.13.3 Solids Content 4.13-5

- 4.13.3.1 Differential Pressure and Ultrasonic Devices 4.13-5
- 4.13.3.2 Nuclear Absorption Meters 4.13-7
- 4.13.3.3 Existing Facilities 4.13-7

4.13.4 SO_2 Measurement 4.13-7

- 4.13.4.1 Existing Facilities 4.13-9

4.13.5 Liquid Level 4.13-12

- 4.13.5.1 Some Design Considerations 4.13-12
- 4.13.5.2 Displacement Instruments 4.13-12
- 4.13.5.3 Differential Pressure Diaphragm 4.13-14
- 4.13.5.4 Capacitance Measurement 4.13-16
- 4.13.5.5 Ultrasonic Linear Height Gauges 4.13-16
- 4.13.5.6 Alarms 4.13-16
- 4.13.5.7 Existing Facilities 4.13-16

4.13.6 Liquid Flow Meters 4.13-18

- 4.13.6.1 Pressure Differential Instruments 4.13-18
- 4.13.6.2 Electronic Devices 4.13-19
- 4.13.6.3 Open Channel Flow 4.13-21
- 4.13.6.4 Flow Controlling and Recording Equipment 4.13-23
- 4.13.6.5 Existing Facilities 4.13-23

4.13.7 Control Panels and Panel Instruments 4.13-25

References 4.13-26

4.13 INSTRUMENTATION

4.13.1 Introduction

To date, lime scrubbers have not been highly instrumented in comparison with many other process plants, and the instrument reliability has been low. The previous poor performance of instrumentation should not be used as a reason for not installing instrumentation on future systems. Instead, it should provide impetus to install better designed process systems with controls and instrumentation capable of functioning properly with normal maintenance. The intent of this section is to present the design engineer with sufficient information to be able to purchase control equipment that is appropriate for the job and as easy as possible to maintain.

The following paragraphs outline five common instrument applications in a lime scrubber and suggest suitable hardware for each. These applications include pH control, solids content, SO_2 measurement, liquid level, and liquid flow.

4.13.2 pH Control

Measurement of pH in the slurry of a lime scrubber is more difficult than in many other industrial applications. Electrodes are fragile devices, easily damaged by the action of an abrasive slurry. Scrubber slurry can also form a deposit on electrodes; this deposit acts as an electrical insulator giving a false value of the electrode potential. Operators should recognize that the pH electrodes of a lime scrubber will require more maintenance and will have shorter lives than in cleaner applications.

4.13.2.1 Reference Electrodes--

There are two types of pH sensor: a dip sensor and a flow-through sensor.[1] The dip sensor is merely inserted into a slurry tank and can be removed for maintenance and calibration. A flow-through sensor depends upon a continuous flow of slurry in the sample line. Both have advantages and disadvantages. The dip sensor is easy to maintain, but cannot be used effectively inside scrubber vessels that must be gas tight. Flow-through sensors depend upon sample lines that, if not well designed, can block. The sensors are also prone to high rates of erosion.

Both types of sensor have operated well in service conditions, but in either case multiple sensors must be employed to ensure accurate measurement.

A major advance in recent years has been the development of pressurizable "nonflowing" reference electrodes constructed of nonbreakable plastics. Although the older "flowing-type" reference electrodes of glass construction are still sold, the newer type is best suited to a slurry application.

Many companies now sell miniaturized electronics packages, which can be serviced easily and quickly by replacement of electronic modules.

No matter whose components are used, wiring between the electrodes and the preamplifier should be as short as possible; one vendor (Uniloc) mounts the preamplifier in the electrode housing to eliminate the short circuits that occur readily in this wiring. This arrangement, however, has the disadvantage of placing the electronics in a wet atmosphere, which could lead to failure of the preamplifier if the housing fails.

All vendors offer either voltage or current output signals, most of which are field-adjustable for both range and span. Almost all this equipment will provide adequate service; none will be trouble-free.

4.13.2.2 Electrode Cleaning Devices--

The ultrasonic type of cleaner should be used with lime scrubber electrodes, since this cleaner is specifically designed for removal of the sort of brittle, insoluble, insulating coatings that can occur in this application. Ultrasonic cleaners work best when operated intermittently with a timed pulse device. This adaption can be purchased as a standard accessory. Both types of sensor can be fitted with ultrasonic cleaning devices, though it is reported that occasionally these have caused the pH probes to break.[1]

4.13.2.3 Electrode Installation--

Installation techniques that have proved beneficial in ensuring pH sensor reliability are presented in Table 4.13-1.

Table 4.13-1. METHODS OF IMPROVING pH SENSOR RELIABILITY[1]

Dip-type sensor probes	Flow-through sensor elements
Provide sufficient vessel agitation.	Provide extremely short sensor lines (1 to 2 ft), at least 1 in. in diameter.
Locate probe away from quiescent zones but provide mechanical support.	Avoid installing sample taps at the bottom of horizontal slurry lines.
Provide external tank for easy access.	Provide piped-up backflushing capability (also can be used for calibrating).
Provide redundant sensors.	Install upstream deflector bar to prevent erosion of the pH cell.
Conduct frequent calibration.	Provide redundant sensors.
	Conduct frequent calibration.

A consistent difficulty with pH measurement is the electrodes and amplifiers are often poorly installed or badly located. In service as severe as in a lime scrubber, the electrodes must usually be cleaned and standardized at least weekly and sometimes daily. The best option is to install dual pH metering systems so calibration can be cross-checked continuously. Experience has shown that installations that are difficult to service receive inadequate service. When it is inconvenient to maintain the electrodes, the operators often neglect the maintenance, and unreliable pH measurement results. A properly designed electrode station should contain a workbench and a cabinet to hold spare parts, small tools, and standardizing solutions. The electrodes should not be mounted directly in the process line; no manufacturer recommends this type of installation. Many lime scrubbers are equipped with immersion-type electrodes. If this design is used, the unit must be readily accessible in an open tank to ensure ease of maintenance. Flow-through electrode holders, if used, should be installed with valves to permit simplified service, since this type also requires frequent service. Flow-through holders should be supplied with slurry by a separate sample pump, a slipstream from the recirculation pump, or by means of a pressure drop across a scrubbing nozzle. There must be enough pressure to produce a flow rate within the range recommended by the electrode manufacturer. One option is to use small-diameter (3/8 in. to 1/2 in.) tubing to maintain high velocity (~10 ft/s). Conversly, some engineers prefer to use large-diameter tubing so that it can be reamed when it plugs. The piping should be as short as possible and arranged so that it completely drains by gravity when shut down. At least two identical electrode assemblies are desirable, with valves and switches arranged for simple crossover to a set of standby electrodes when a set requires service or a calibration check. All amplifiers and calibration controls should be installed at the electrode station to permit one man to perform the necessary adjustments. This eliminates the need for communication between the control room and the maintenance man during calibration.

4.13.2.4 pH Controller--

The signal from a pH measurement instrument is usually sent to a main control panel, where a control instrument is used to adjust the rate of lime feed. Although more sophisticated control systems are built into some lime scrubbing FGD systems, simple feedback control of pH has been used predominately to date. The pH controller need not be purchased from the same manufacturer that supplies the electrodes and amplifiers. Since only the larger of the several specialty instrument companies that make dependable pH measurement equipment produce controllers in sufficient quantity to maintain quality control, in some instances more than one vendor should be used.

Electronic controllers have an advantage over pneumatic instruments in that their signal conversion takes place at the valve, which is a more favorable position in the loop, and their operation is slightly faster. Either type should be purchased as a three-mode instrument incorporating proportional, integral, and derivative action, because even if three-mode control is not required at the time, flexibility is maintained at a minimal additional cost. Special electronic nonlinear controllers specifically designed for difficult pH applications are also available. These instruments were described in Section 3.0 of this data book. Although it may be difficult to tune a nonlinear controller to match the process characteristics, the pH control should improve.

Equipment for measuring pH is made by several U.S. companies, including Beckman, Foxboro, Great Lakes, Leeds and Northrup, and Universal Interloc. Several other companies make part of the equipment and resell other components from both U.S. and foreign manufacturers. Some of the foreign-made electrodes give excellent service in difficult applications, especially certain ones made in Japan and Switzerland and sold by laboratory supply jobbers such as Fisher Scientific Co. and A. H. Thomas. All brands are electrically compatible with U.S. amplifiers.

4.13.2.5 Performance History--

Data on operational pH control systems are presented in Table 4.13-2. Brief descriptions of pH system performance are given below:

Phillips and Elrama--These stations have no automatic pH controls. The instruments only monitor the pH of the slurry. Problems with pH at Phillips and Elrama are usually caused by breakdowns in the lime slurry supply systems. Neither station reports pH measurement problems.

Bruce Mansfield--At this station, the pH electrodes are mounted in a 1-in. slipstream from the recirculation line, with electrodes located on a platform with difficult access. Because cleaning and maintenance are difficult, problems with dirty and broken electrodes occur repeatedly. The station is redesigning the electrode station.

Green River and Cane Run--Six sets of pH electrodes are installed in the recirculation tank. Each set is checked against the others daily. Recalibration and repairs are done as needed. Control of pH is excellent, and they report no maintenance problems.

Conesville No. 5--At this station, the pH electrodes are submersed in a trough on the bleed-off line from the recirculation loop. The pH is pneumatically controlled by changing the slurry flow rate with change in the pH. Maintenance is not a major problem.

Paddy's Run--Two sets of pH electrodes are installed in the recirculation tank. The major operating problem has been the buildup of a film on the probe, which has to be cleaned manually once every 3 to 4 days.

4.13.3 Solids Content

Scrubber installations should include instrumentation for continuous control or recording of variables related to solids content.

4.13.3.1 Differential Pressure and Ultrasonic Devices--

Slurry density can be directly measured with special differential pressure instruments, but a 6-ft liquid depth is needed to measure a 0.1 specific gravity span. Ultrasonic devices directly measure the percentage of suspended solids. Vibrating reed instruments measure the dampening effect of the slurry on vibrations from an electrically driven coil.

Table 4.13-2. pH CONTROL INSTRUMENTATION.

Facilities	pH electrode assembly					
	Mfr.	Type	Model	Location	Single/multiple	Cleaning type
Conesville No. 5 Columbus and Southern Ohio	Foxboro	Immersion	NR	Recirc. line, bleed trough	Single	NR
Elrama Duquesne Light	Uniloc	Flow-through	324	Recirc. line	Single	Ultrasonic
Phillips Duquesne Light	Uniloc	Flow-through	324	Recirc. line	Single	Ultrasonic
Green River Kentucky Utilities	Uniloc	Immersion	324	Recirc. tank	Multiple (1)	Manual
Cane Run Louisville Gas and Electric	Uniloc	Immersion	321	Recirc. tank	Multiple (1)	Manual
Paddy's Run Louisville Gas and Electric	Uniloc	Immersion	321	Recirc. tank	Multiple (2)	Manual
Bruce Mansfield	Uniloc	Flow-through	324	Recirc. line	Single	Manual
Pennsylvania Power						

NR - Not recorded

4.13.3.2 Nuclear Absorption Meters--

Nuclear absorption meters, which measure the degree of absorption of gamma rays from a radioactive source, are preferred for this service. These instruments do not physically contact the slurry; they are strapped to a pipe through which the slurry is flowing. They have the minor disadvantage of producing a signal that is not linear with solids content unless the unit purchased contains an electronic linearizer. The nuclear meter can be precalibrated by theoretical calculations if an accurate chemical analysis of the slurry being metered is used, but vendor data for "average" slurry should not be used, since this may produce a calibration with a very large error. Each manufacturer specifies a source size range in millicuries for each pipe size diameter. It is advisable to purchase on the high side of the range, since smaller sources produce erratic or sluggish output signals.

By government regulation, an NRC license certifying familiarity with radiation safety practices is required before any extensive maintenance can be performed on nuclear instruments. Since manufacturers of nuclear equipment are small companies with limited service facilities, licensing some members of the plant service group is strongly recommended.

Three manufacturers of nuclear absorption instruments are Kay-Ray, Ohmart, and Texas Nuclear.

4.13.3.3 Existing Facilities--

Table 4.13-3 presents solids content design information from several FGD installations.

The nuclear density meter is a low-maintenance instrument. The only problem with these meters has been their inaccuracy and inconsistency. At Green River and Cane Run facilities, the density measurements are often verified by manual sampling and testing. Bruce Mansfield, however, reports fairly reliable operations with its nuclear density meters. At Elrama, Philips, and Paddy's Run the solids content is checked by periodic manual sampling only.

4.13.4 SO_2 Measurement

Lime scrubbing systems are usually provided with instrumentation to measure the SO_2 content of gases entering and leaving the scrubber. As with most instrumented analytical measurements, the devices are costly and the operating principles are sophisticated. Available instruments operate on one of three principles:

Table 4.13-3. SOLIDS CONTENT INSTRUMENTATION

Facilities	Density meter Mfr.	 Type
Conesville No. 5 Columbus and Southern Ohio	Nuclear	K-Ray Texas Nuclear
Elrama Duquesne Light	None	NA
Phillips Duquesne Light	None	NA
Green River Kentucky Utilities	Nuclear	Ohmart
Cane Run Louisville Gas and Electric	Nuclear	Texas Nuclear
Paddy's Run Louisville Gas and Electric	None	NA
Bruce Mansfield Pennsylvania Power	Nuclear	Texas Nuclear

NA - Not applicable

NR - Not recorded

(1) Coulometry - Gas is exposed to an electrolyte through a semipermeable membrane. Chemical changes in the electrolyte are measured by electrochemical oxidation at a sensing electrode.

(2) Absorption spectrophotometry - Light is passed through a gas, and the degree of absorption of certain infrared or ultraviolet wavelengths is measured.

(3) Emission spectrography of chemiluminescence and fluorescence - Molecules or atoms are energized by exposure to high-intensity ultraviolet radiation or an electric charge; they emit light in specific wavelengths, and the amount of emitted light is measured.

The most consistent difficulty with the operation of an SO_2 analyzer has been the difficulty of withdrawing a sample of gas and preconditioning it for feed to the analyzer cell. Sampling systems not only sometimes introduce errors into the reading, but can also become plugged and corroded very quickly. The intent of the sampling system is to remove solid particulates and water droplets while avoiding condensation of water vapor. In practice, as the water collects it continues to absorb SO_2 and oxygen and creates a strong sulfuric acid solution. Solids preferentially collect on other precipitated solids and form scale. Careful design of the sampling system is therefore required. Electrostatic precipitators or filters, heated lines to prevent condensation, and a suitable back flush to prevent filter and sample pipe blockage are suggested.[2] This system is shown schematically in Figure 4.13-1.

On the other hand, spectrophotometric instruments are available that, by eliminating the sampling system, may provide better service. One type has a probe, which, because of its location, might be difficult to maintain. Another type uses a beam of light that passes completely across a section ductwork, but it is difficult ot calibrate.[3]

The SO_2 concentration is generally recorded on a strip chart potentiometric recorder. The operating record will be of use to the plant operator in optimizing scrubber performance, and if the mechanical problems that have plagued these units can be solved, they will undoubtedly be used in closed-loop control of lime feed rate.

4.13.4.1 Existing Facilities--

Table 4.13-4 presents design information on SO_2 meters installed in lime scrubber facilities. The only device currently in service is the absorption spectrometer.

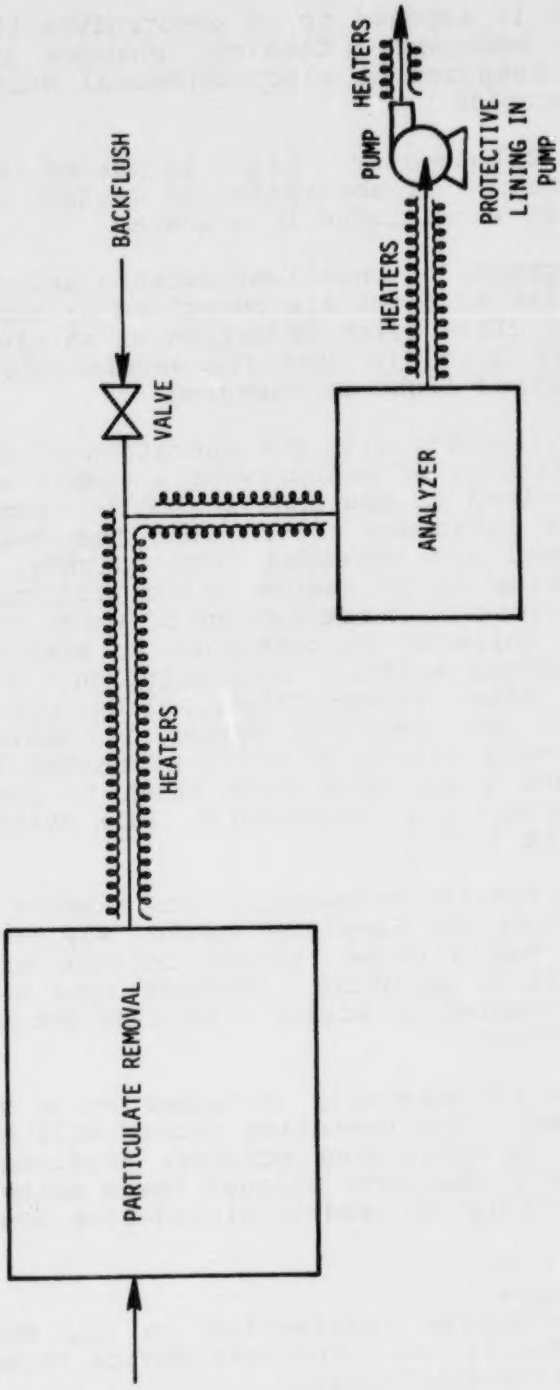

PARTICULATE REMOVAL
HEATERS
VALVE
BACKFLUSH
ANALYZER
HEATERS
PROTECTIVE LINING IN PUMP
PUMP
HEATERS

Figure 4.13-1. Ideal SO_2 sampling system.[2]

Table 4.13-4. SO$_2$ INSTRUMENTATION

Facilities	SO$_2$ meter		
	Mfr.	Model	Sample type
Conesville No. 5 Columbus and Southern Ohio	DuPont Lear-Siegler	460 NR	Wet Dry
Elrama Duquesne Light	Environmental Instruments	NR	In situ Dry
Phillips Duquesne Light	Environmental Instruments	NR	In situ Dry
Green River Kentucky Utilities	DuPont	460	Wet
Cane Run Louisville Gas and Electric	DuPont	460 A	Dry
Paddy's Run Louisville Gas and Electric	DuPont	460 A	Dry
Bruce Mansfield (Pennsylvania Power)	DuPont	460 A	Dry

NR - Not recorded

All the plants using Dupont SO_2 meters report very high maintenance on the analyzer systems. Moisture condensation on the probe, plugging of the sample lines, and frequent calibration requirements are some of the major operational problems. Under an EPA contract, York Corporation is investigating some modifications to blowback and the cleaning of sample lines at the Bruce Mansfield facility. The modifications have been successful in reducing maintenance somewhat.

4.13.5 Liquid Level

In a lime scrubber, level control is usually used to release excess slurry into a pond or thickener and may regulate the quantity of water recycle. Local pneumatic control instruments (instruments that have no external signal input) are often used for simple level control applications (e.g., water tank levels); when they are used, high- and low-level alarms are also usually supplied to inform the control panel operator of malfunctions. If electronic liquid level sensors are employed, as on more complex applications such as the slurry tank, it is most convenient to locate the controller on the control panel; therefore, supporting alarms are of less importance. Hardware for control of liquid level should be dependable rather than absolutely accurate.

4.13.5.1 Some Design Considerations--

Dependability is the most important criterion. Therefore, the use of such systems as bubble tubes requires careful design to prevent blockages, since they can easily become plugged in lime slurry applications. Devices using mechanical floats are not recommended for use with a slurry that may form deposits. The displacement principle and the force-balanced, differential-pressure diaphragm measurement of liquid level are probably the most satisfactory for this application. Capacitance instruments are also proving dependable. Ultrasonic meters are also available.

4.13.5.2 Displacement Instruments--

If a scrubber system contains a separate reaction tank with an open top, an internal displacement transmitter is a good choice for level measurement (Figure 4.13-2). A displacement instrument is basically a simple scale, measuring the weight of a stainless steel cylinder that is partly immersed in the liquid. The cylinder does not float in the liquid, but as the level rises or falls, its apparent weight decreases or increases in proportion to the volume of liquid displaced by its submerged portion. The instrument is mounted above the tank, and the displacement cylinder is suspended in a pipe well or behind a baffle to protect it from surface agitation. If liquids or

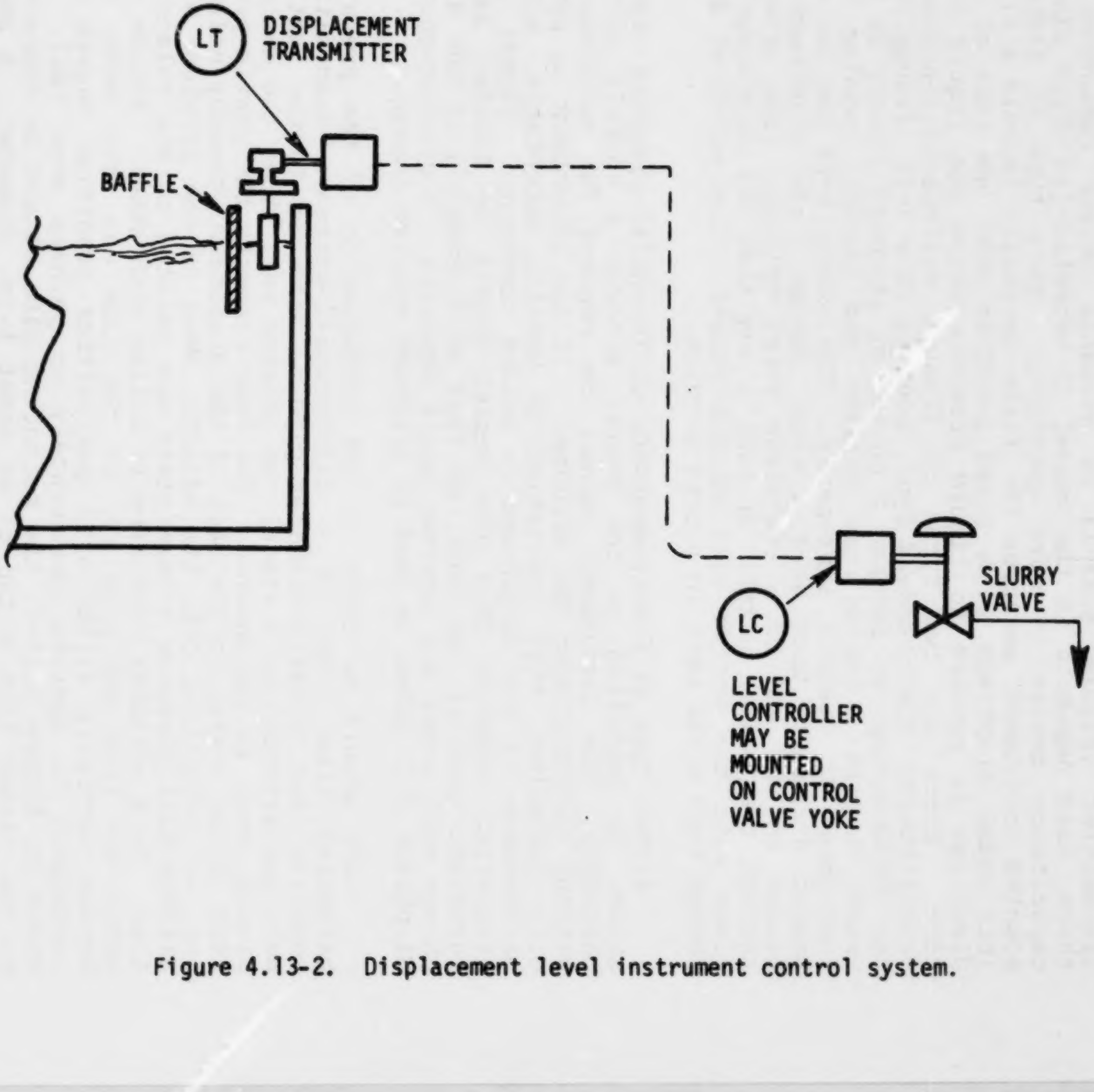

LT
DISPLACEMENT
TRANSMITTER
BAFFLE
LC
LEVEL
CONTROLLER
MAY BE
MOUNTED
ON CONTROL
VALVE YOKE
SLURRY
VALVE

Figure 4.13-2. Displacement level instrument control system.

solids do not impinge onto the parts of the instrument above the surface of the liquid, and if any surface deposits are periodically removed, a displacement transmitter will be trouble-free.

4.13.5.3 Differential Pressure Diaphragm--
For measurement of liquid level in a closed vessel such as the body of a scrubber, a flange-mounted, differential-pressure transmitter (Figure 4.13-3) is suitable unless formation of thick, hard deposits in the vessel is expected (in which case a capacitance device is more suitable). This type of flange-mounted instrument measures the force necessary to hold a flexible metal diaphragm in a fixed position when one side of the diaphragm is exposed to liquid pressure below the liquid surface. There are two types of flanged differential-pressure transmitters. The standard type, mounted on a 3-in. flange, has the disadvantage of forming a pocket of stagnant slurry in the vessel nozzle. Solids can collect and harden, causing the instrument to operate improperly. The other type has an extended diaphragm that uses a 4-in. flange. The diaphragm is placed on the end of a stainless steel cylinder that extends through the vessel nozzle in such a way that the diaphragm is flush with the inside wall of the vessel. The extended diaphragm type works best in slurry service.

Either type of flange-mounted, differential-pressure transmitter is installed on the vessel without a shutoff valve; therefore, the instrument cannot be removed for maintenance without shutting down the scrubber. If the instrument is properly installed, this limitation is usually acceptable, since maintenance of the diaphragm is seldom necessary. Proper installation requires that the vessel nozzle be located in a turbulent zone of the tank, so that mild scouring of the diaphragm will occur and prevent scale deposits. A plastic-coated diaphragm will often be used to minimize erosive damage.

Care should be taken in the installation of the pressure balancing line. Use of a differential-pressure transmitter requires that a small-diameter pipe be attached to the instrument and extended to a vessel tap located well above the maximum liquid level in the vessel. The line connects the static pressure in the vessel to the back of the diaphragm, thereby balancing, or cancelling out, its effect. Many of the problems with differential-pressure transmitters are related to the balancing line. In a scrubber, the line is filled with water. Solids can enter the line and plug it, or the line can lose water and become partially filled with gas; either condition causes the instrument to operate inaccurately or perhaps even fail. As shown in Figure 4.13-3, the balancing line should be connected to the vessel into a tap of at least 1-in. diameter. A small rotameter should be installed to purge a continuous stream of

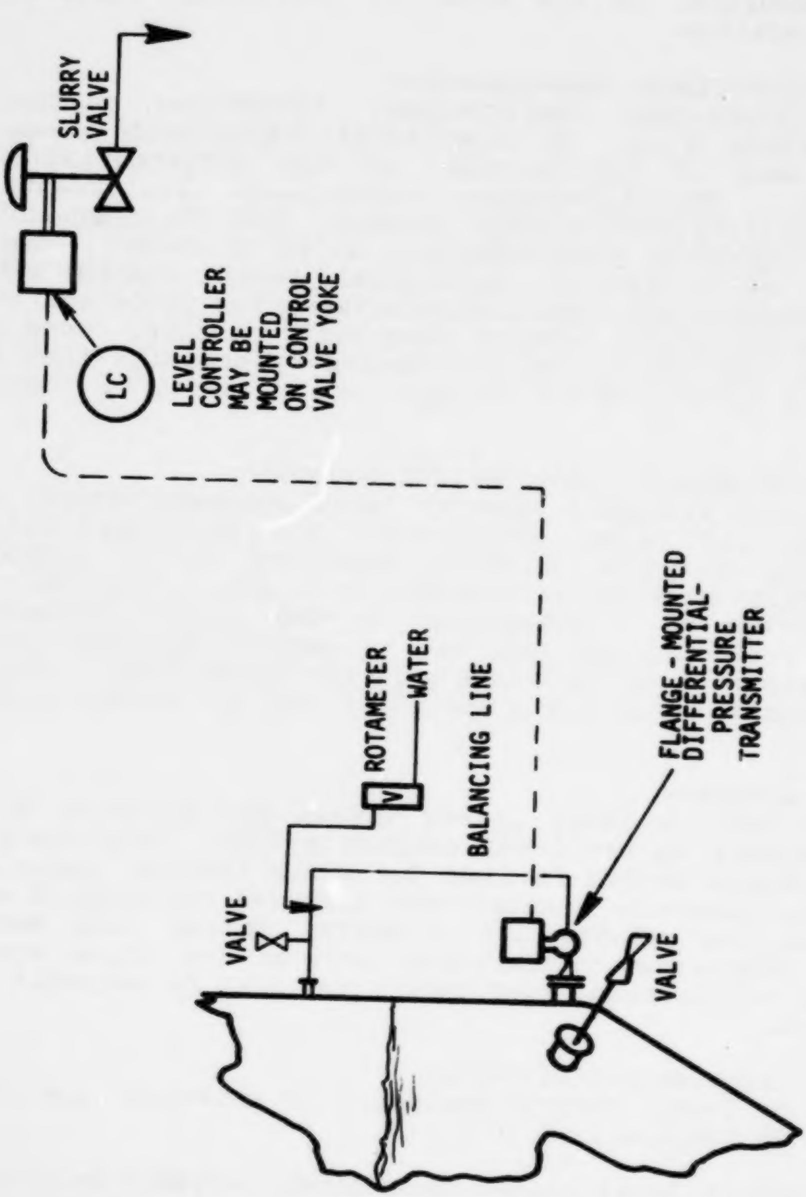

SLURRY VALVE
LC
LEVEL CONTROLLER MAY BE MOUNTED ON CONTROL VALVE YOKE
ROTAMETER
WATER
BALANCING LINE
VALVE
FLANGE - MOUNTED DIFFERENTIAL-PRESSURE TRANSMITTER
VALVE

Figure 4.13-3. Flange-mounted differential-pressure level control system.

water into the tap and thus prevent accumulation of solids. It is also desirable to provide a tap into the vessel, located near and at the same elevation as the transmitter. In addition a valved tap should be supplied in the balancing line. These connections can be used with a water-purged manometer to check calibration of the instrument or to attach a substitute water-purged transmitter in the event of instrument failure during scrubber operation.

4.13.5.4 Capacitance Measurement--

For closed-tank applications, throttling control from instrumentation based on electrical capacitance measurement overcomes many of the problems of the differential-pressure transmitter. Throttling-type capacitance instruments from various suppliers vary widely, however, and the dependable ones are quite expensive (approximately $3000 to $4000). These instruments, which use an electrical probe coated with TFE (Teflon), measure the capacitance between the probe and the tank wall with a relatively complex electronic circuit. Good quality capacitance instruments are unaffected by deposits that accumulate on the probe and by the presence of spray or vessel agitation.

4.13.5.5 Ultrasonic Linear Height Gauges--

These are available from at least one manufacturer (Badger Meter, Inc., of Tulsa, Oklahoma). The fact that Ultrasonic Systems have no parts actually submerged in the liquid makes them virtually free of maintenance problems. Ultrasonic energy is transmitted by a transducer to the liquid surface. The signal is reflected and received by another separate transducer and the elapsed time is converted into fluid level. The meters are constructed from stainless steel and are sealed with epoxy resin.[4]

4.13.5.6 Alarms--

High- and low-level alarms inform the operator if a malfunction occurs in the level control system. Completely separate instruments should be used for alarm sensing, especially if differential-pressure transmitters are used for control sensing. Capacitance instruments are a better choice than mechanical float or electrical conductance devices for alarm actuation. Ultrasonic or vibrating reed probes may also be suitable in this application.

4.13.5.7 Existing Facilities--

Data on level control equipment in existing lime scrubbers are shown in Table 4.13-5.

The liquid level gauges have given reliable service at all the facilities but Green River, where inaccuracy of the gauge has sometimes necessitated manual control of pond water returns.

Table 4.13-5. LIQUID LEVEL INSTRUMENTATION

Facilities	Level gauge	
	Mfr.	Type
Conesville No. 5 Columbus and Southern Ohio	Foxboro	Transmitter
Elrama Duquesne Light	Taylor	NR
Phillips Duquesne Light	Taylor	NR
Green River Kentucky Utilities	B/W	Float
Cane Run Louisville Gas and Electric	NR	NR
Paddy's Run Louisville Gas and Electric	NR	NR
Bruce Mansfield Pennsylvania Power	Foxboro	Bubbler

NA - Not applicable

NR - Not recorded

4.13.6 Liquid Flow Meters

Measurement of liquid or slurry flow rates is vital to the optimization of a process plant. Although lime scrubber systems have not used slurry flow meters to date, their adoption is expected. The flow rate of fresh lime slurry is perhaps the most important control application, but flow rate of recycle slurry and of slurry drawoff to a thickener are also important points of application.

Several physical principles are used to measure liquid or slurry flow rate. Available instruments fall into three broad categories: one based on mechanical measurement of pressure differential, one encompassing various electronic measurements, and the third designed for measurement in open channels. Each category has its specific applications.

4.13.6.1 Pressure-Differential Instruments--

Pressure-differential instruments are best suited to clean water flowing through piping under pressure. Examples of these devices include orifice meters, flow nozzles, pitot tubes, Dall tubes, venturi meters, target meters, and rotameters. Target meters contain a metal plate in the flowing stream; this device must not be used with any liquid that may contain abrasive particles. Rotameters are intended primarily for local indication of small flow rates, such as water feed to a lime slaker. The principle of measurement used in a rotameter creates a mechanical force that is too weak for a dependable connection to signal transmission accessories. All of the other types of mechanical flow measurement instruments mentioned above require the use of small ports connected into the process stream. If the liquid contains suspended solids, the lead lines will become plugged unless correctly designed. A continuous purge of fresh water is needed if these instruments are to be used even with thin slurries. The instruments also contain stagnant water, which can freeze easily in winter weather; this necessitates the use of heating jackets or insulation to prevent freezing.[5] Pressure-differential instruments measure neither volumetric nor mass flow rate, and their measurement is inaccurate unless the density of the flowing stream remains constant. Measurements are also inaccurate unless the instruments are installed with the required lengths of straight piping both upstream and downstream from the meter location.

Despite their disadvantages, pressure-differential instruments are in wide use. They are not only less expensive initially than electronic types, but they can also be calibrated accurately using only standardized calculations and simple test equipment. For these reasons, they are often used for slurries, even though maintenance costs are high. Single-port cast venturi meters are least affected by abrasive wear and suffer least from lead line plugging; they are about as expensive as the electronic types. Some of the insert-type venturi meters and flow nozzles operate almost as well and are significantly less costly. Multiport venturis, pitot tubes, and most types of special flow tubes are more easily plugged by slurries. Sharp-edged orifices are worn away quickly by abrasive slurry. Quadrant-edged orifice plates are the least expensive practical slurry measurement devices; they work best in vertical lines (Figure 4.13-4).

Except for target meters and rotameters, pressure-differential instruments require the use of a differential-pressure transmitter, which need not be purchased from the same manufacturer as the meter itself. Force-balanced transmitters, such as those made by Bailey, Fischer and Porter, and Foxboro, are most often used, but a newer electronic-transmission principle unit sold by Honeywell and Rosemount is gaining acceptance.

Equipment to provide freshwater purge of lead lines should include two small purge rotameters with each transmitter. Purge water must be filtered. If filtered water is distributed in copper or stainless steel tubing, a single filter can be used. Alternatively, individual filters may be supplied with each transmitter.

4.13.6.2 Electronic Devices--

Electronic measurement of flow rate can be accomplished with vortex-shedding instruments, ultrasonic transmission devices, Doppler-effect ultrasonic meters, and electromagnetic flow meters. The first two are unsuited to abrasive slurry.

Doppler-effect meters--The Doppler-effect ultrasonic meter is a fairly new development that is intended for slurry applications. Its principal advantage is that the sensors are cemented to the outside of the pipe through which the slurry is flowing; there is no penetration of the pipe. Badger Meter, Inc. (Tulsa, Okla.) supplies ultrasonic flow meters as a spool section for attachment to metal, plastic, or asbestos cement pipes, or for use in open channels with variable fluid height. Accuracies within 2 percent are reported.[4] The meters have a linear output and a meter factor of 1.00.[6]

Hersey Products (Spartanburg, S.C.) also produces an ultrasonic flowmeter. It operates on a different principle and is designed only for closed pipes. It requires at least 2 percent solids or an injected gas bubble flow to operate. It is therefore less versatile than the Badger Meter product. It is suitable for use on most pipes and has an accuracy within 5 percent.[7]

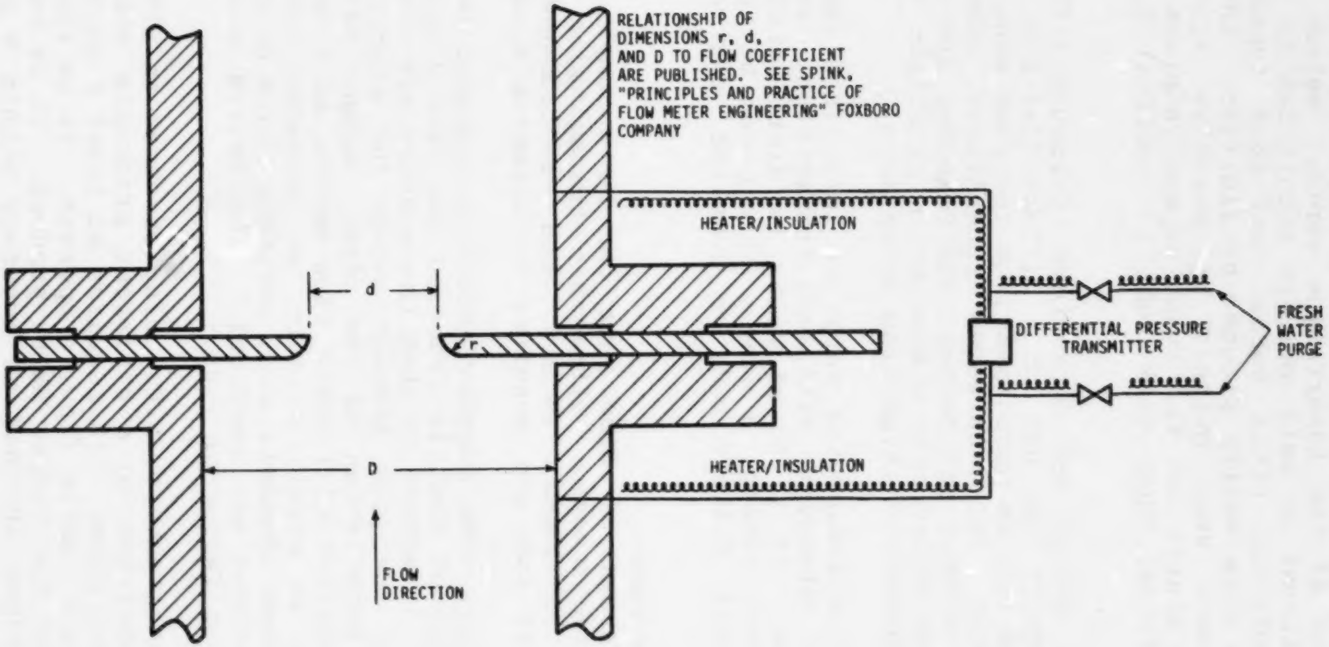

RELATIONSHIP OF DIMENSIONS r, d, AND D TO FLOW COEFFICIENT ARE PUBLISHED. SEE SPINK, "PRINCIPLES AND PRACTICE OF FLOW METER ENGINEERING" FOXBORO COMPANY
HEATER/INSULATION
d
r
DIFFERENTIAL PRESSURE TRANSMITTER
FRESH WATER PURGE
HEATER/INSULATION
D
FLOW DIRECTION

Figure 4.13-4. Quadrant-edged orifice plate.

Note: Relationship of dimensions 4, d, and D to flow coefficient are published. See Spink, "Principles and Practice of Flow Meter Engineering," Foxboro Company.

Tech/Sonics (Houston, Tex.) manufactures a meter similar to that from Hersey Products. It requires gas bubbles or suspended solids in the stream and has an accuracy within 2 percent. Portable or dedicated versions are available.[8]

Electromagnetic devices--The electromagnetic flowmeter, or "magnetic meter," is the best proven instrument available for the measurement of pressurized water slurries (Figure 4.13-5). It consists of a stainless steel pipe section lined with an electrically insulating material. Two metal electrodes protrude through the lining, and a coil is arranged to supply a magnetic flux perpendicular to the slurry flow direction. The slurry itself acts as a conductor that cuts across the flux, thereby inducing an electrical potential between the electrodes. When amplified, the signal is adjusted to indicate the true volumetric flow rate of slurry. The signal is linear with flow rate and can be recorded on a uniformly graduated chart. The magnetic meter does not require installation in a straight piping run and introduces no pressure drop into the flowing stream. The lining can be made of an abrasion-resistant material; polyurethane resin is recommended by most manufacturers, but Neoprene synthetic rubber is probably better in meters smaller than 4 in. Teflon is available, but is not as resistant to abrasion. Electrodes can be of any metal; hardened Type 316 stainless steel is the usual manufacturer's standard and is suitable for most scrubber services. Magnetic meters should be recalibrated at least annually. Magnetic meters, which are expensive instruments, are made by several companies, but Brooks, Fischer and Porter, Foxboro, and Taylor market them most actively.

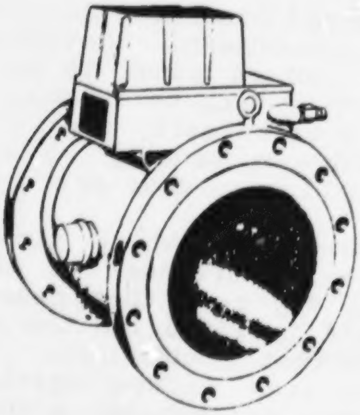


Figure 4.13-5. Typical magnetic flow meter.

Less expensive devices are also made that use the electromagnetic principle. One, which is usually called the insert-type magnetic meter, consists of a coil in a thin probe which sets up a magnetic flux inducing a voltage in two electrically insulated sections of the probe casing. This instrument measures the velocity of the slurry in a small region near the tip of the probe. The other magnetic-type instrument consists of a small, conventional magnetic meter totally immersed in a larger pipeline. It measures the velocity of the portion of the flow that passes through the small meter. The only advantage of these two instruments is their lower cost. Their disadvantage is the uncertainty of their calibration accuracy.

4.13.6.3 Open Channel Flow--

Open channel flow measurements are suited to streams that can be made to flow by gravity, such as the feed slurry to a thickener. These devices are most often used in plants with a civil engineering design basis, such as waste treatment plants, but they are equally suitable for use in chemical processes such as lime scrubbing. A relatively inexpensive calibrated flume is installed in a freely flowing, unpressurized pipeline or channel. Measurement of the level of the flowing liquid in the throat section of the flume is directly related to fluid flow rate. The best known device for this application is the Parshall flume, although others are made to fit into either rectangular channels or partly filled, circular pipes. Most are sold as preassembled fiberglass and plastic constructions. They may also be constructed of poured concrete using forms sold for this purpose. A variety of mechanical and pneumatic instruments are available that fit onto the flumes to transmit a signal related to flow rate. Ultrasonic devices are also available for open channel flow measurement, as discussed in Section 4.13.6.2.

4.13.6.4 Flow Controlling and Recording Equipment--

Signals from flow measurement instruments are usually brought to a centralized control panel to be recorded or used directly in the control of a scrubber. Most flow measurement signals change rapidly and erratically over a rather wide band; therefore, a chart record can usually be read with greater accuracy than can an indicating pointer or a digital instrument.

Signals from pressure-differential flow instruments are nonlinear, since they are proportional to the square root of flow rate. These signals may be either passed through square root extraction instruments to linearize the signal or recorded on chart paper with square root graduations. It is customary in many electric power industries to use square root extractors with all these measurements, since these signals are most often used in a boiler plant for ratio computation or cascade control, where linearization is necessary. In a lime scrubber, however, where some flow signals are not associated with complex control loops, the chart record may be read more accurately without square root extraction. If adjusted improperly, extractors can introduce substantial error at the low end of the scale.

Signals from at least one of the brands of ultrasonic equipment are linear.[4,6] This is another advantage of the use of ultrasonic systems.

4.13.6.5 Existing Facilities--

Flow metering equipment used at existing lime scrubbers is shown in Table 4.13-6.

The most widely used liquid flow meter is the magnetic type. Cane Run and Paddy's Run facilities have had no operational problems, whereas at Green River there was initially a minor pluggage problem. At Bruce Mansfield, it was found that the magnetic flowmeter generates heat when shut off and causes lining material failures. Foxboro has alleviated this problem by changing the lining material on the flowmeters.

4.13.7 Control Panels and Panel Instruments[9]

Control panels and panel instruments do not need detailed discussion, since the utility industry already has detailed specifications.

It is important to emphasize, however, that uniformity in design and spares in a new system will simplify operation and maintenance. Similarly, uniformity between a retrofit system and the existing boiler will also prove beneficial unless the existing panel system has caused too many problems.

Systems should be designed with consideration to operability, efficiency, ease of maintenance, and safety.

Table 4.13-6. FLOW INSTRUMENTATION

Facilities	Flow meter	
	Mfr.	Type
Conesville No. 5 Columbus and Southern Ohio	Foxboro	Magnetic
Elrama Duquesne Light	Foxboro	Magnetic
Phillips Duquesne Light	Brooks Brooks	Magnetic ΔP
Green River Kentucky Utilities	Fischer Porter	Magnetic
Cane Run Louisville Gas and Electric	Foxboro Brooks	Magnetic
Paddy's Run Louisville Gas and Electric	Foxboro	Magnetic
Bruce Mansfield Pennsylvania Power	Foxboro Brooks	Magnetic

REFERENCES

1. Jones, D. G., A. V. Slack, and K. S. Campbell. Lime/Limestone Scrubber Operation and Control Study. EPRI (RP630-2). April 1978.

2. Private communication with P. S. Lowell, P. S. Lowell and Associates, September 1978.

3. Private communication with T. Moraski, EPRI, August 1978.

4. Badger Meter. Product literature, Tulsa, Oklahoma.

5. Private communication with P. S. Lowell, P. S. Lowell and Associates, September 1978.

6. Private communication with A. H. Barnes, Colorado State University, August 1978.

7. Hersey Products. Product literature, Spartanburg, South Carolina, September 1978.

8. Private communication with Tech/Sonics, Houston, Texas, September 1978.

9. Private communication with P. S. Lowell, P. S. Lowell and Associates, September 1978.

SECTION 5

BID REQUEST/EVALUATION

5.1 INTRODUCTION

This section presents information to assist a utility engineer in the preparation of bid requests for an FGD system and subsequently to evaluate bids received. This information supplements a utility's normal process for bid requests and evaluations on proposed capital expenditures.

CONTENTS

5.2 DESIGN BASIS

Page

5.2.1 Coal and Ash Analyses 5.2-1
5.2.2 Boiler Conditions 5.2-2
5.2.3 Gas Flow Rate and Temperature 5.2-3
5.2.4 Particulate Control Strategy 5.2-4
5.2.5 SO_2 Loading and Emission Regulations 5.2-4
5.2.6 Lime Properties 5.2-5
5.2.7 Makeup Water Composition 5.2-5
5.2.8 Waste Disposal Requirements 5.2-5
5.2.9 Miscellaneous Information 5.2-5

5.2 DESIGN BASIS

To submit bids that are cost-effective and responsive to a utility's needs, prospective FGD system suppliers require specific information in many areas; thus, utility companies that provide sufficient information are in a better position to obtain an optimum emission control system. Bid requests should be specific so that bids received from the various vendors are of similar content and scope for ease of comparison and should contain the following:

- Equipment of the proper type, size, and materials of construction
- The required sparing capacity (redundancy)
- Guarantees to meet applicable emission regulations at all operating conditions
- Well-defined maintenance requirements

A successful design depends on a few key parameters that are essential to FGD system design:

- Coal and ash analyses
- Boiler conditions
- Gas flow rate and temperature
- Particulate control technology
- SO_2 loading and emissions regulations
- Lime properties
- Makeup water composition
- Sludge disposal requirements (if sludge disposal is within the scope of the bid request)

5.2.1 Coal and Ash Analyses

An extensive sampling and analysis program is recommended, particularly when coal from more than one coal seam is used. The coal analysis, used in conjunction with boiler firing practices, can be used to define accurately the composition of the flue gas to be treated. Prospective bidders should be supplied with a proximate and an ultimate coal analysis form with mean values and ranges noted. The following example is a sample coal analysis form.

Coal Analysis

Proximate analysis, as received, percent by weight	Mean value	Range of values
Moisture		
Ash		
Volatile matter		
Total		
Sulfur		
Heating value, Btu/lb		

Ultimate analysis, as received, percent by weight	Mean value	Range of values
Moisture		
Ash		
Sulfur		
Nitrogen		
Carbon		
Hydrogen		
Oxygen		
Chlorine		
Total		

It is also recommended that a fly ash alkalinity evaluation be performed and the results provided to prospective bidders. The method of measurement used in determining this alkalinity should be identified. The fly ash might have sufficient alkalinity to enhance SO_2 removal; if so, a lime/fly ash system (several are in operation) that saves considerably on the cost of reagent (when compared with a system using lime alone) can be designed.

5.2.2 Boiler Conditions

As previously mentioned, the boiler conditions, in conjunction with the nature of the coal fired, determine the composition of the flue gas being treated. Items that should be provided are boiler type, coal size when fired, coal firing rate, Btu input rate, excess air in the boiler, and any air leakage expected throughout the plant life. Boiler material balance calculations that identify concentrations in the gas stream should be performed on at least the following:

- SO_2
- SO_3
- O_2
- CO_2
- H_2O
- Chloride
- Fly ash

The reader is referred to Section 2.3 as an aid to performing these material balance calculations.

Because FGD systems operate best when running in a steady state mode, and swing conditions greatly increase the probability of costly problems, it is important to provide prospective bidders with the expected variability in any of the above conditions. Boiler operating conditions are no exception.

5.2.3 Gas Flow Rate and Temperature

The unit size of an FGD system is usually classified by power generating capacity, i.e., megawatts (MW). In a bid specification, however, the only meaningful method of determining size is the specification of flue gas flow rate and temperature. Flow rate and temperature should be provided from several points along the gas path as it exits the boiler, such as the boiler outlet, the inlet and outlet of the economizer, air heater, particulate collection device, and any other equipment preceding the SO_2 absorption train.

The most important location for specifying flow rate and temperature is the inlet to the proposed FGD system, as this is the key parameter in determining sizing of gas handling equipment (ducts, quencher, absorber, fan, reheater, and stack). This parameter has often been incorrectly specified, leading to underdesigned FGD systems. Again it is essential to delineate any variability in gas flow and temperature.

The primary purpose in purchasing an FGD system is to meet the SO_2 emission regulation for the life of the boiler plant. One major factor that is not considered frequently, however, is future air leakage. The effects of the increased air flow due to air leakage are as follows: increased requirement for fan capacity, increased pump capacity to maintain design level for L/G, increased module cross-sectional area to maintain design level for gas velocity, increased piping capacity, increased tank capacity to handle the increased liquor flows and levels, increased demister loading (more liquor being entrained and the gas traversing the demister at higher velocities), and increased reheater requirements.

FGD system suppliers do not guarantee FGD system operations throughout the life of the boiler plant because there are too many variables beyond their control. Usually the vendor guarantee applies only through the test run. Because the utility will be required at all times to comply with the emission regulation, the following options should be evaluated:

- Request the bidders to design a system that will remove sufficient SO_2 at the increased air flows to be expected as air leakage worsens throughout the plant life, based on expected air flows (provided by the utility) throughout the plant life. The bidder should not be requested to make a guarantee, but simply to consider the expected flow rates. This procedure should increase the chances for adequate SO_2 removal over the life of the plant.

- Realize that the increased air flow problem will probably occur, and plan to operate the boiler at a reduced load when it does occur. The primary determinant of boiler load would be air flow to the FGD system. This scheme of reducing boiler load as a function of air flow to the air pollution control equipment would follow normal utility planning methodology wherein ever-decreasing amounts of power generation are required from any particular boiler.

5.2.4 Particulate Control Strategy

The particulate controls that precede the proposed absorption train in the gas flow loop, inlet and outlet particulate loadings, and the regulation for final particulate emission and opacity should be specified. Expected variations at the scrubber inlet should also be discussed.

5.2.5 SO_2 Loading and Emissions Regulations

The expected SO_2 loading at the FGD inlet and the required SO_2 loading, with the specified averaging time, at the stack exit should also be included. To ensure compliance, the utility may desire to specify an outlet loading that is lower than the applicable regulation.
For example, if the regulation is 1.2 lb SO_2/million Btu input, the utility may specify 1 lb SO_2/million Btu input to allow a safety factor because of time averaging requirements. To summarize, the following stack conditions should be specified:

- SO_2 flow, lb/million Btu input
- Particulate flow, lb/million Btu input
- Mist loading, gr/scf

- Plume opacity, percent (usually controlled by determining removal efficiency required to meet regulation)
- Stack exit temperature, °F (if desired)

5.2.6 Lime Properties

If a lime supply has been obtained, the bid specifications should give information about the reagent such as magnesium content, size, composition, reactivity, and slaking rate.

5.2.7 Makeup Water Composition

A complete analysis of the makeup water supply should be provided. The water source should be named, e.g., service water, river water, cooling tower blowdown. Sodium, magnesium, and chloride ion concentration, pH, sulfite/sulfate content, and solids level are especially important. In addition, the amount of water discharge (if any) allowable under local regulations should be specified. This amount, evaporation losses, and interstitial water exiting with the sludge permit calculation of makeup water requirements.

5.2.8 Waste Disposal Requirements

Regarding waste disposal requirements, the utility should specify the proposed disposal site and the desired quality of the final product with respect to solids content, pH, leaching characteristics, and impact strength (minimal if sludge is being landfilled, high if it is to be used for building foundations). EPRI's Sludge Manual provides greater detail concerning waste disposal requirements.

5.2.9 Miscellaneous Information

Other items that should be included in bid specifications are:

- Annual weather and temperature conditions. Inadequate cold weather protection has caused extensive downtime in existing systems.

- Retrofit restrictions (if applicable). Space limitations, current fan placement and materials of construction, and current duct and stack placement, sizing, and materials of construction should all be specified.

- Startup date required. If a rapid job is planned, it could significantly affect the cost of the system.

CONTENTS

5.3 GUARANTEE REQUESTS

	Page
5.3.1 General	5.3-1
5.3.2 SO_2 Removal	5.3-2
5.3.3 Particulate Removal Efficiency	5.3-2
5.3.4 Mist in the Outlet	5.3-3
5.3.5 Power Consumption	5.3-3
5.3.6 Reheat Energy Consumption	5.3-4
5.3.7 Lime Consumption	5.3-4
5.3.8 Water Consumption	5.3-4
5.3.9 Waste Streams	5.3-4
5.3.10 Turndown Ratio	5.3-5
5.3.11 Availability	5.3-5
5.3.12 General	5.3-6

5.3 GUARANTEE REQUESTS

5.3.1 General

In the past, utilities sometimes were given vague process guarantees with their purchase of an FGD system. In some instances, these guarantees proved to be less than binding because they were not specific in covering the possible range of operating conditions. Currently, however, major system suppliers are willing to supply detailed guarantees in several important areas.

A utility requesting bids for an FGD system should simultaneously request the accompanying guarantees. These guarantees should not only ensure satisfactory process and equipment performance, but also set limits on certain operating parameters. For example, clearly stipulated guarantees for SO_2 and particulate removal relate to satisfactory process and equipment performance. In addition, guarantees on items such as power consumption, reheat energy consumption, lime consumption, and waste stream quality and quantity establish a basis for projecting accurate operating costs.

This process of requesting guarantees provides two advantages for the utility. It allows an in-depth comparison of the strength and scope of the guarantees among the various bids and permits operating costs to be predicted accurately.

This section includes a discussion of guarantees for the following items:

- SO_2 removal efficiency
- Particulate removal efficiency
- Mist in the outlet gas stream
- Waste stream quality/quantity
- Power consumption
- Reheat energy consumption
- Lime consumption
- Water consumption
- Turndown ratio
- System availability

In requesting guarantees, it is essential to specify measurement procedures in detail to avoid later, potentially costly, misunderstandings. In flue gas or waste stream sampling, items such as test port location and accessibility, sampling procedure, analysis procedure, data reporting procedure, and assignment of financial responsibility of conducting sampling should be clearly defined.

Another important concept is to require as many guarantees as possible to be consistent with the applicable environmental regulations, especially for SO_2 removal, particulate removal, mist in the outlet, and waste stream quality.

5.3.2 SO_2 Removal

SO_2 removal guarantees are requested most often. In the past, guarantees were written specifying that the FGD system would effect a certain percentage of SO_2 removal, usually for a specific coal sulfur content. The percent removal was such that, for the specified coal, sufficient SO_2 would be removed from the flue gas to meet the applicable regulation; however, problems can occur because there can be significant deviations in the coal sulfur content and flue gas flow rate. Both of these factors affect required SO_2 removal and the operation of the FGD system. Bidders should therefore be requested to guarantee meeting the SO_2 emission regulation (usually expressed in allowable lb SO_2/million Btu input) over the entire range of operating conditions set forth in the design basis.

Regulations being considered by the U.S. Environmental Protection Agency (EPA) for new utility boilers include an averaging time over which the emissions must not exceed a certain value. If a regulation of this type becomes effective, the utility should ascertain that the system is guaranteed to meet it.

As mentioned earlier, it will be important to specify in the guarantee request the sampling procedure (probably EPA Method No. 6) that will be used and the exact location of test ports (according to the EPA test procedure). In addition, all conditions that require testing for compliance should be specified in the request. For instance, if the regulation requires the unit to be tested under varying boiler load conditions (e.g., 50%, 100%), this should be included in the guarantee request.

5.3.3 Particulate Removal Efficiency

Even though particulate removal is effected in an ESP, baghouse, or scrubber upstream of the FGD system, particulate discharge can present a problem when particulate matter generated by slurry carryover is not removed in the mist eliminator.

To avoid particulate emission problems, one of three types of guarantee is suggested. The most straightforward guarantee applies the appropriate particulate emission regulation to the FGD system discharge; however, system vendors are reluctant to guarantee the absorber system outlet particulate concentration if they are not supplying the primary upstream particulate control system.

The second method, and one in use in several current applications, guarantees that the particulate concentration at the FGD system outlet is no greater than that at the inlet, based on the inlet concentration complying with the regulation.

The third strategy requires a certain particulate removal in the FGD system and applies if the upstream particulate control system does not bring the unit into compliance by itself.

5.3.4 Mist in the Outlet

Absorber discharge loading is a critical factor because it affects reheat load, downstream corrosion, downstream scaling, and outlet particulate loading. This is a difficult quantity to measure, however, because the accuracy of the measuring methods is not known. Any guarantee concerning mist in the flue gas must be carefully reviewed, realizing there is no proven method of analysis.

It may be better to require extensive design data and project outlet mist loading. Since partial plugging is the usual cause of excessive mist carryover, it is more of an operating problem.

5.3.5 Power Consumption

Only electric power usage by fans, pumps, motors, instrumentation, lights, etc., are addressed under this heading. Reheat energy consumption, sometimes calculated as a portion of the total boiler derating resulting from FGD operations, is discussed in Section 5.3.6.

There are several types of power consumption guarantees. Sometimes a partial power consumption guarantee is given by guaranteeing maximum pressure drop across the FGD system. Because fan horsepower is directly proportional to pressure drop, this type of guarantee limits electric power consumption by the fans only.

Another form, and perhaps the most logical, guarantees maximum power consumption (e.g., the plant will consume a maximum of ____ kWh.); however, this method does not relate power usage to a specific process parameter.

A third form specifies a maximum percentage of the total plant power production to be used by the FGD system (e.g., the scrubber plant will consume no more than ___ percent at full boiler load, ___ percent at half boiler load).

5.3.6 Reheat Energy Consumption

Once again the simplest and most requested guarantee for reheat energy consumption specifies a guaranteed maximum fuel consumption in Btu per hour. Two refinements of this simple approach warrant consideration. The first relates fuel consumption to scrubber inlet gas flow; thus, the guarantee would be for a maximum Btu consumption per volume of gas (Btu/scfm). Another refinement stipulates minimum acceptable downstream temperature at this heat flow. Whatever is guaranteed, the location and methods of energy and gas flow measurement, as well as the test interval, should be specified.

5.3.7 Lime Consumption

The guarantee for lime consumption is usually a maximum usage rate (lb/h), which can be related to a process variable (the rate of SO_2 removal). The guarantee should be written in pounds of lime consumed per pound of SO_2 removed.

The lime usage rate is difficult to measure unless the plant is equipped with a gravimetric-type lime feeder in advance of the slaker. It is therefore important to specify the test method for lime feed rate measurement. One method measures rate in gallons per minute with a magnetic flowmeter and the density with a nuclear density meter. Both of these pieces of equipment are expensive and are seldom included in the bid package. A second method operates the lime slurry system as a batch process during the test run. (Each batch must be measured and sampled for solids content.)

5.3.8 Water Consumption

The amount of water consumed by the process may be guaranteed, but it is better not to specify this parameter. The critical item in the plant water balance is the need, in many areas, to run closed loop. If this is the case, it is advantageous to specify closed-loop operation and let the vendor use as much water as needed. Closed-loop operation should be clearly defined at all boiler loads and SO_2 concentrations for which the scrubber would be operated.

5.3.9 Waste Streams

The waste streams that are acceptable should be specified in the request because the plant material balance is highly influenced by these streams. Thus, it should be specified whether the plant will produce dry landfill, use a settling pond, or operate open or closed loop. If regulations permit the plant to discharge, then the limits of wastewater quality should appear in the guarantee. Again, the utility should specify the sampling and analysis method as well as at what level of boiler operation these waste streams should be measured.

5.3.10 Turndown Ratio

The utility should consider specifying that prospective bidders guarantee a maximum turndown ratio. (Maximum turndown ratio is defined as follows: the ratio of maximum flow rate to minimum flow rate.) It is important that the guaranteed ratio consider the lowest expected boiler load at which power can be efficiently produced. The utility needs to be assured that it could operate at the lowest desirable boiler load and still expect satisfactory FGD operation. This will be site-specific, and therefore no number is offered as a suggested maximum turndown ratio. The turndown ratio should be identified by system as well as by vessel.

Bidders should be requested to clarify one important point: when operations are proceeding at maximum turndown, what will be the FGD system response to a need to rebuild the load? The bidders should specify the expected FGD system lag time as boiler load increases. Also, they should specify whether the available operating conditions increase in a step-function manner or in a continuous manner. Thus, if a maximum turndown ratio of 4 to 1 is guaranteed, the bidders should indicate whether the boiler load could fall anywhere in the range from 25 percent to 100 percent, or whether it would only be possible to operate at certain discrete loads (e.g., 25%, 50%, 75%, and 100%.)

The turndown ratio guarantee will be closely related to the SO_2 removal guarantee at varying boiler loads and will also relate to the utilities and reagent consumption guarantees, as well as closed-loop guarantees.

5.3.11 Availability

The commonly accepted definition of availability is the hours the FGD system is available for operation (whether operated or not) divided by the hours in a period, expressed as a percentage. A recent U.S. EPA survey* prepared by the Industrial Gas Cleaning Institute reported that of 12 major system suppliers responding to a question about guaranteeing availability, seven indicated that they would guarantee an availability (system performance) factor. Five system suppliers said they would not give such a guarantee. Five of the seven suppliers providing positive response indicated that they would guarantee an availability of 90 percent.

---

* Flue Gas Desulfurization Systems Manufacturer's Survey. EPA-68-02-2532, Industrial Gas Cleaning Institute, Stamford, Connecticut, November 1977.

It is therefore recommended that the utility request an availability guarantee from the prospective bidders. When the bid evaluation procedure is initiated, this can be an essential area of comparison.

5.3.12 General

In evaluating the proffered guarantees it is important to evaluate the financial liability being assumed by the various bidders to achieve the guarantee levels. As an example, consider the situation wherein two vendors have each guaranteed an availability (as defined in the bid specification) of at least 90 percent for one year. One vendor, however, sets a limit on his expenditures to meet the guaranteed level of availability (e.g., the supplier shall expend no more than $1,000,000 to achieve the guarantee level), and the other supplier is willing to make expenditures up to an amount equal to the total system cost.

CONTENTS

5.4 EQUIPMENT AND INSTRUMENTATION

Page

5.4.1 Introduction 5.4-1

5.4.2 Venturi Scrubber 5.4-1

    5.4.2.1 Corrosion 5.4-1
    5.4.2.2 Erosion 5.4-3
    5.4.2.3 Plugging 5.4-3

5.4.3 Venturi Recirculation Pumps 5.4-3

    5.4.3.1 Corrosion 5.4-3
    5.4.3.2 Erosion 5.4-3
    5.4.3.3 Pump Seals 5.4-5
    5.4.3.4 Suction Head 5.4-5

5.4.4 Venturi Recirculation Tank 5.4-5

    5.4.4.1 Corrosion 5.4-5
    5.4.4.2 Erosion 5.4-5
    5.4.4.3 Tank Size 5.4-7

5.4.5 Presaturator 5.4-7

    5.4.5.1 Corrosion/Erosion 5.4-7
    5.4.5.2 Nozzle Construction 5.4-7

5.4.6 Absorber 5.4-7

    5.4.6.1 Pressure Drop 5.4-10
    5.4.6.2 Scaling and Plugging 5.4-10
    5.4.6.3 Erosion 5.4-11
    5.4.6.4 Corrosion 5.4-11

5.4.7 Absorber Recirculation Pumps 5.4-12

    5.4.7.1 Corrosion 5.4-12
    5.4.7.2 Erosion 5.4-12
    5.4.7.3 Pump Seals 5.4-12
    5.4.7.4 Suction Head 5.4-12
    5.4.7.5 Maintenance Simplicity 5.4-14

CONTENTS (continued)

Page

5.4.8 Absorber Recirculation Tank 5.4-14

    5.4.8.1 Corrosion/Erosion 5.4-14

5.4.9 Mist Eliminator 5.4-14

5.4.10 Soot Blowers 5.4-18

5.4.11 Stack Gas Reheater 5.4-20

    5.4.11.1 In-line Reheat 5.4-21
    5.4.11.2 Direct-fired Reheat 5.4-21
    5.4.11.3 Indirect Reheat 5.4-21
    5.4.11.4 Bypass Reheat 5.4-21

5.4.12 Dampers 5.4-23

5.4.13 Duct Work 5.4-24

5.4.14 Booster Fan 5.4-27

    5.4.14.1 Corrosion 5.4-27
    5.4.14.2 Cleaning and Inspection 5.4-27
    5.4.14.3 Temperature Rise 5.4-27

5.4.15 Lime Silos 5.4-29

    5.4.15.1 Materials of Construction 5.4-29
    5.4.15.2 Conveying Systems 5.4-29
    5.4.15.3 Closed Construction 5.4-29

5.4.16 Lime Feeder 5.4-29

    5.4.16.1 Conveying Mechanism 5.4-29
    5.4.16.2 System Shutdown 5.4-30

5.4.17 Lime Slaker 5.4-30

    5.4.17.1 Lime Type 5.4-30
    5.4.17.2 Slaker Type 5.4-30
    5.4.17.3 System Reliability 5.4-32
    5.4.17.4 Miscellaneous 5.4-32

5.4.18 Lime Stabilization/Storage Tank 5.4-32

CONTENTS (continued)

Page

5.4.19 Lime Slurry Feed Pump 5.4-32

  5.4.19.1 Abrasion 5.4-35
  5.4.19.2 Pump Seals 5.4-35
  5.4.19.3 Lime Slurry Feed Control 5.4-35

5.4.20 Freshwater Pump 5.4-35

5.4.21 Thickener 5.4-38

  5.4.21.1 Corrosion 5.4-38
  5.4.21.2 Solids Concentration 5.4-38
  5.4.21.3 Clarification 5.4-38
  5.4.21.4 Recirculation 5.4-39
  5.4.21.5 Solids Removal 5.4-39

5.4.22 Flocculant Proportioning Pump 5.4-39

5.4.23 Thickener Underflow Pump 5.4-39

5.4.24 Thickener Overflow Pump 5.4-42

  5.4.24.1 Corrosion 5.4-42
  5.4.24.2 Pump Seals 5.4-44

5.4.25 Thickener Overflow Tank 5.4-44

  5.4.25.1 Corrosion 5.4-44
  5.4.25.2 Erosion 5.4-44
  5.4.25.3 Tank Size 5.4-44

5.4.26 Centrifuges 5.4-47

  5.4.26.1 Materials of Construction 5.4-47
  5.4.26.2 Rotational Speed 5.4-47
  5.4.26.3 Conveyor Speed 5.4-47

5.4.27 Vacuum Filters 5.4-49

  5.4.27.1 Materials of Construction 5.4-49
  5.4.27.2 Drying Time 5.4-49
  5.4.27.3 Barometric Legs 5.4-49
  5.4.27.4 Filter Medium 5.4-49

CONTENTS (continued)

Page

5.4.28 Filtrate or Centrate Pump 5.4-49

- 5.4.28.1 Erosion 5.4-51
- 5.4.28.2 Corrosion 5.4-51
- 5.4.28.3 Pump Seals 5.4-51

5.4.29 Fixation Additive Silos 5.4-51

- 5.4.29.1 Materials of Construction 5.4-51
- 5.4.29.2 Conveying Systems 5.4-53

5.4.30 Fixation Tank or Pug Mill 5.4-53

- 5.4.30.1 Corrosion 5.4-53
- 5.4.30.2 Erosion 5.4-53
- 5.4.30.3 Tank Size 5.4-53

5.4.31 Sludge Disposal Pump 5.4-55

- 5.4.31.1 Corrosion 5.4-55
- 5.4.31.2 Erosion 5.4-55
- 5.4.31.3 Pump Seals 5.4-55
- 5.4.31.4 Pumping Distance and Head 5.4-55

5.4.32 Sludge Conveying System 5.4-57

- 5.4.32.1 Belt Conveyor 5.4-57
- 5.4.32.2 Screw Conveyor 5.4-57

5.4.33 Pond Water Return Pump 5.4-59

- 5.4.33.1 Erosion 5.4-59
- 5.4.33.2 Corrosion 5.4-61
- 5.4.33.3 Pump Seals 5.4-61
- 5.4.33.4 Pump Placement 5.4-61

5.4.34 pH Sensors and Controller 5.4-61

- 5.4.34.1 Probe Location 5.4-63
- 5.4.34.2 Probe Type 5.4-63
- 5.4.34.3 Nonlinear Control 5.4-64

5.4.35 Level Controllers 5.4-64

- 5.4.35.1 Displacement Controllers 5.4-64
- 5.4.35.2 Differential Controllers 5.4-64
- 5.4.35.3 Capacitance Controllers 5.4-66

CONTENTS (continued)

Page

4.3.36 Flowmeters 5.4-66

5.4.36.1 Magnetic Flowmeters 5.4-68
5.4.36.2 Nuclear Density Sensors 5.4-68

5.4.37 SO_2 Analyzers 5.4-68

5.4.37.1 Extractive Analyzers 5.4-70
5.4.37.2 Probe Locations 5.4-70
5.4.37.3 Sample Line Maintenance 5.4-70
5.4.37.4 In Situ Analyzers 5.4-70

5.4.38 Pressure Sensors and Controller 5.4-71

5.4.39 Temperature Sensors and Controller 5.4-71

5.4.40 Control Valves 5.4-75

5.4 EQUIPMENT AND INSTRUMENTATION

5.4.1 Introduction

This section presents a description of the major pieces of equipment that comprise a lime FGD system, a description of the service these components will experience, factors to be considered when specifying the components, and sample specification sheets for them. Tables 5.4-1a and 5.4-1b list the equipment and instrumentation addressed in this section.

5.4.2 Venturi Scrubber

A venturi scrubber is a gas-atomized spray device; i.e., it uses a moving gas stream to atomize liquid into droplets and then to accelerate the droplets. High gas velocities of 200 to 400 ft/s impart a high relative velocity between the gas and the liquid drops and promote particle collection by inertial impaction. In a venturi scrubber, liquid is introduced at the entrance to the throat through several nozzles that are directed radially inwards.

Efficiency of particle collection increases with throat velocity and liquid-to-gas (L/G) ratio. Because pressure drop increases as the square of the velocity, it is better engineering practice to use a high L/G ratio rather than a high gas velocity to obtain a given overall efficiency. L/G ratios ranging from 5 to 20 gal/1000 ft^3 have been used. The bid requestor should specify a minimum L/G value that will ensure a droplet concentration sufficient to sweep the gas stream completely.

The following factors should be considered in the design of the venturi scrubber:

1. Corrosion
2. Erosion
3. Plugging

5.4.2.1 Corrosion--

Corrosion from the acid contaminants and solids buildup is a major operating problem in venturi scrubbers. Selection of proper corrosion resistant materials is critical. This is also the area of the scrubber that will have the highest chloride concentration, if it is maintained as a separate loop. Proper design of the venturi inlet opening can greatly reduce corrosion in this critical zone. Continuous flushing of all inlet nozzles averts particulate buildup, whereas the uniform wetting of walls reduces damage from localized acid concentrations. If corrosion resistant materials are not used, it is most important that continuous control of the pH of the recirculating slurries be maintained during operation.

Table 5.4-1a. EPRI LIME FGD SYSTEMS DATA BOOK EQUIPMENT LIST

Particulate control subsystem

- Venturi scrubber
- Venturi recirculation pumps
- Venturi recirculation tanks

Sulfur dioxide absorption subsystem

- Absorber
- Absorber recirculation tank
- Absorber recirculation pumps
- Mist eliminator
- Soot blowers
- Reheaters
- Dampers
- Duct work
- Fan

Sludge disposal subsystem

- Reaction tank pump
- Thickener
- Flocculant proportioning pump.
- Thickener underflow pump
- Thickener overflow pump
- Thickener overflow tank
- Vacuum filter or centrifuge
- Filtrate or centrate return pump
- Pug mill or fixation tank
- Sludge disposal pump
- Fixation additive silo
- Fixation additive feeder
- Sludge conveying system (belt and screw conveyor)
- Front end loader or bulldozer
- Pond water return pump

Lime preparation subsystem

- Storage silos
- Feeders
- Slakers
- Stabilization/storage tank
- Lime slurry feed pumps
- Fresh water pump

Table 5.4-1b. EPRI LIME FGD SYSTEMS DATA BOOK INSTRUMENTATION LIST

Instrumentation List
pH sensors and controllers
Level controls
Flowmeters
SO_2 analyzers
Pressure sensors and controllers
Temperature sensors and controllers
Control valves

5.4.2.2 Erosion--

The inlet section of a venturi scrubber is subjected to high-velocity erosion. It is often made of a much higher grade alloy, e.g., Inconel 625, than is the main scrubber body, which may be 316 ELC (extra low carbon).

5.4.2.3 Plugging--

The nozzles may plug frequently as a result of grit material. Plugging can be avoided by installing strainers in the recirculation line upstream from the nozzles.

Table 5.4-2 is a typical specification to be completed by the architect/engineer, or by the equipment supplier for the venturi vendor.

5.4.3 Venturi Recirculation Pumps

The venturi recirculation pump is used to supply a high volume of recycled water to the venturi in those systems that remove particulate matter. The pumps are usually designed to share the load between two pumps, with an installed spare. Since the venturi recirculation pump is critical for complying with particulate regulations, care should be taken in the design to ensure reliable operation. The system can be designed so that slurry or liquid is pumped from the bottom of the venturi vessel or from a recirculation tank located under the venturi. The following factors should be considered in specifying venturi recycle pumps:

1. Corrosion
2. Erosion
3. Pump seals
4. Suction head

5.4.3.1 Corrosion--

In all systems, whether the venturi is designed to remove particulate matter or not, the venturi recycle pumps operate in a corrosive atmosphere. In a particulate-only system without pH control, the pH is normally about 1. Rubber-liners or high-alloy steel liners are therefore required for corrosion resistance. If less corrosion resistant materials are used, some form of pH control is needed.

5.4.3.2 Erosion--

The fly ash removed in the venturi is a highly erosive material containing small particles of silica and alumina derived from fly ash. Rubber-lined pumps and pumps constructed of an erosion resistant alloy (such as Ni-Hard) are suitable for this erosive service; however, if the pH is not maintained above 4, Ni-Hard pumps should not be used.

Table 5.4-2. EPRI LIME FGD SYSTEM DATA BOOK
VENTURI SCRUBBER SPECIFICATIONS

CHECKED BY ____________ DATE ________ SPEC. NO. ____________

COMPUTED BY ____________ DATE ________ PROJ. NO. ____________

COMPANY ______________________________ LOCATION ____________________

EQUIPMENT NO. ____________ FOR USE ON ____________ TOTAL NO. REQ'D. ____________

SUPPLIER ________________________ P.O. NO. ________ PRICE EACH $__________

1 GENERAL DESCRIPTION
2
3

GENERAL INFORMATION

4 SPECIFICATIONS: FABRICATION TEST
5 WORKING PRESSURE: PSIG AT F. DESIGN PRESSURE: PSIG AT°F.
6 WIND LOAD SEISMIC LOAD
7 EST. WEIGHT: LBS EMPTY LBS. FILLED WITH H_2O

CONVERGING SECTION

8 DIAMETER OR CROSS SECTION X AT INLET
9 LENGTH: WALL THICKNESS:
10 MATERIALS: SHELL LINING THK.
11 CORROSION ALLOWANCE SEAMS: WELDED BRAZED
12 TYPE OF FLANGED JOINTS

THROAT

13 DIAMETER: OR CROSS SECTION: X
14 LENGTH: WALL THICKNESS
15 MATERIALS: SHELL LINING THK.
16 CORROSION ALLOWANCE SEAMS: WELDED BRAZED
17 TYPE OF LIQUID INLET:

DIVERGING SECTION

18 DIAMETER OR CROSS SECTION X AT OUTLET
19 LENGTH: WALL THICKNESS
20 MATERIALS: SHELL LINING THK.
21 CORROSION ALLOWANCE SEAMS: WELDED BRAZED
22 TYPE OF FLANGED JOINTS

SUPPORT

23 TYPE WEIGHT MAT'L. AND THK.

NOZZLES

	USE	NUMBER	SIZE	LOCATION
24	GAS INLET			
25	GAS OUTLET			
26	LIQUID INLET			
27	MANHOLE			
28	MANOMETER			
29	SPARE			
30	LIQUID OUTLET			

PROCESS INFORMATION

31 GAS COMPOSITION(%): CO_2 O_2 H_2O SO_x NO_x
32 GAS lb/hr, ACFM AT °F
33 PARTICULATE lb/hr, SIZE DISTRIBUTION: MEAN DIA μm VARIANCE
34 REMOVAL EFFICIENCY: REQUIRED DESIGN
35 GAS PRESSURE DROP: IN. WG.
36 LIQUID: lb/hr, COMPOSITION:
37 LIQUID: RECIRCULATION GPM, BLEED GPM
38 LIQUID pH: RECIRCULATION BLEED

REMARKS AND SPECIAL DETAILS:

5.4.3.3 Pump Seals--

Since the solids in the slurry contain highly erosive particles, sealing with water to prevent erosion of the pump shaft is required. Individually controlled seal water sources should be specified.

5.4.3.4 Suction Head--

This pump should be designed with a net positive suction head (NPSH) greater than 15 ft to prevent outgassing. In addition to reducing the flow rate, cavitation caused by outgassing can destroy a rubber-lined pump.

Table 5.4-3 is a typical specification to be completed by the architect/engineer, or by the equipment supplier for the pump vendor.

5.4.4 Venturi Recirculation Tank

The venturi recirculation tank holds the liquor that falls through the venturi. The highly abrasive slurry contains fly ash removed from the flue gas. In systems in which lime is not added to the slurry, the pH is very low (approaching 1). Several factors must be considered in the design of a venturi absorber. These include:

1. Corrosion
2. Erosion
3. Tank size

5.4.4.1 Corrosion--

The tank must be designed for a low-pH environment. Rubber-lined carbon steel or 316L stainless steel should be used to prevent attack by sulfurous/sulfuric acid. Chloride attack of the stainless steel is not a problem if the tank is properly designed to prevent deposition of solids or scale. If deposits or scale do not form, then chloride attack under the scale will not occur. (To prevent evolution of SO_2 from the surface of the liquor in systems operating at low pH, the tank should be covered.)

5.4.4.2 Erosion--

To prevent erosion, proper design or rubber linings are needed. The fly ash slurry will cause abrasion (erosion/corrosion) of the stainless steel if the tank is not designed to minimize velocity at liquid inlets to the tank. Therefore, in systems where there is no lime neutralization, rubber lining may be the safer choice.

5.4.4.3 Tank Size--

The tank should be sized to provide sufficient NPSH and adequate slurry supply to the venturi recirculation pump.

Table 5.4-3. EPRI LIME FGD SYSTEM DATA BOOK
VENTURI RECIRCULATION PUMP SPECIFICATIONS

COMPANY ____ LOCATION ____
EQUIPMENT NO. ____ FOR USE ON ____ TOTAL NO. REQUIRED ____
SUPPLIER ____ P.O. NO. ____ PRICE EACH $ ____

GENERAL INFORMATION

TYPE ____
DUTY: CONTINUOUS ____ INTERMITTENT ____
SERVICE ____

PROCESS INFORMATION

LIQUID: ____
DESIGN FLOW: NORMAL ____ MAX ____ GPM
PUMPING TEMPERATURE ____ °F
SP. GR. @ PUMPING TEMPERATURE ____
VISCOSITY @ PUMPING TEMPERATURE ____
VAPOR PRESS. @ PUMP TEMP. ____ (FT.LIQ.)
PH VALUE ____
CORROSIVE MATERIAL ____
SOLIDS (MAX. DIA.) ____

HYDRAULIC INFORMATION ____ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+) ____
STATIC SUCTION LIFT (-): HEAD (+) ____
SUCTION FRICTION HEAD (-) ____
TOTAL SUCTION HEAD (17+18+19) ____
STATIC DISCHARGE HEAD ____
DISCHARGE FRICTION HEAD ____
DISCHARGE PRESS. ABOVE LIQ. (ABS.) ____
TOTAL DISCHARGE HEAD (21+22+23) ____
TOTAL DYNAMIC HEAD (24-20) ____
NPSH AVAILABLE (20-13) ____
NPSH REQUIRED ____

PUMP

MANUFACTURER ____
RPM ____
PERFORMANCE CURVE ____
SERIAL NO. ____
BPH @ SERVICE CONDITIONS
@ MAX. FLOW FOR IMPELLER ____
ROTATION @ DRIVE SHAFT END ____
COPIES REQUIRED OF: ____
PERFORMANCE CURVES ____
DIMENSION DRWGS. ____
OPERATING AND MAINTENANCE INSTRUCTIONS ____

MATERIALS

MATERIAL CODE - EXTERNAL CASING ____ INTERNAL PARTS ____

I - CAST IRON	INTERNALS CODE	I	B	S	C
B - BRONZE	IMPELLER	I	B	S	C
S - STEEL	INNER CASE PARTS	I	B	S	C
C - 11-13% CHROME	SLEEVE (PACKED)	Ch	Ch	Af	Af
A - ALLOY	SLEEVE (SEAL)	C	C	C	C
h - HARDENED	WEAR RINGS		B	Ch	Ch
f - FACED	SHAFT	S	S	S	S
	LANTERN RING				
	PACKING GLAND				

SUCTION CONN: SIZE ____ POSITION ____
DISCHARGE CONN: SIZE ____ POSITION ____
CONN. RATING ____ TYPE ____
PACKING TYPE ____
LANTERN RINGS ____ MATERIAL ____
COOLING ____
BEARINGS: TYPE ____ GREASE ____ OIL ____
IMPELLER: TYPE ____ SIZE FUR. ____ MAX. ____
VENT CONN: ____ DRAIN CONN. ____

FLUSHING CONNECTION: ____

DRIVER ____

FURNISHED WITH PUMP ____ BY OTHERS ____
TYPE: ____
FRAME: ____
MANUFACTURER: ____
ENCLOSURE ____
VOLTS ____ PHASE ____ CYCLE ____
HP ____ RPM ____
BEARINGS ____ LUBRICATION ____
COUPLING GUARD ____

NOTES:

Table 5.4-4 illustrates a typical specification to be completed by the utility, architect/engineer, or system supplier for the tank vendor.

5.4.5 Presaturator

The presaturator cools the flue gas to its adiabatic saturation temperature prior to contact with the scrubbing slurry. This increases SO_2 removal efficiency and minimizes the potential for corrosion and scaling at the slurry/gas interface areas.

The following factors should be considered in the design of the presaturator:

1. Corrosion/erosion
2. Nozzle construction

A possible specification sheet is shown in Table 5.4-5.

5.4.5.1 Corrosion/Erosion--

The presaturator is subjected to abrasion from the fly ash, recirculating solids in the scrubbing system, and corrosion from possible chloride attack. If no particulate scrubber is used, acidic pH may accentuate corrosion.

5.4.5.2 Nozzle Construction--

The potential of erosive attack in the spray nozzles is often an area of concern. The use of refractory spray nozzles, such as those constructed of silicon carbide, is recommended if erosion becomes a problem.

5.4.6 Absorber

The absorber is the piece of equipment designed to remove SO_2 from the flue gases. Gas-liquid contact is affected by various internal configurations in an absorbing tower. The countercurrent flow arrangement is the one most commonly used. However, EPRI is presently evaluating a cocurrent scrubbing concept at the Shawnee test facility of TVA and has done pilot investigations at TVA's Colbert facility. The reader is referred to EPRI's report "Cocurrent Scrubber Evaluation: TVA's Colbert Lime/Limestone Wet Scrubbing Pilot Plant." Some first-generation absorbers used a variable-throat venturi design; however, SO_2 absorption efficiency was low because of the brief liquid-gas contact times. In addition, the use of a venturi throat configuration for SO_2 removal has led to significant problems in the form of solids deposition in the regions of wet-dry interface. It is also inherently difficult to fabricate a venturi without crevices and angles in the weld areas, and these rough regions have experienced solids deposition. When solids deposition occurs, corrosion stress on those metal surfaces is increased.

Table 5.4-4. EPRI LIME FGD SYSTEM DATA BOOK
VENTURI RECIRCULATION TANK SPECIFICATIONS

Sheet of

R E V

CUSTOMER ____________________ JOB NO. ____________________

PLANT LOCATION ____________________ EQUIPT. NO. ____________________

SERVICE ____________________ FILE NO. ____________________

____________________ P.O. NO. ____________________

Type of Tank ____________________

Size:__________ Diam.__________ Height__________ Capacity__________

GENERAL NOTES

1) For required capacity as shown, Mfg. to advise diameter and height of tank for the most economical utilization of plate.
2) Nozzle orientation to be furnished later.
3) Nozzle location and design tube furnished later with mechanical design.
4) Ladder Clips & Ladder:
   __________ Inside __________ Outside
5) Design P.__________ Design T__________
6) Paint ____________________
7) Lining - Fiberglass or rubber Note 1

NOZZLES	MARK	NO.	SIZE	RATING
Inlet				
Outlet				
Drawoff Elbow				
P & V Vent				
Level Gage				
Thermowell				
Roof Manhole				
Shell Manhole				

DESIGN DATA

Tank Material Min. Plate Thick SP GR

Corrosion Allowance: Shell in.; Bottom in.; Roof in.

APPURTENANCES (BY)

Level Gage or Gate Column: Yes No Type

Make Fig. or Equal Float

Pressure & Vacuum Vent Valve: Yes No Pressure oz.

Make Fig. or Equal Vacuum oz.

Gage Hatch: Yes No. Make Fig. or Equal

Thermometer Well: Yes No Length In

Make Model or Equal Material

Thermometer: Yes No Stem Length In

Make Model or Equal Range

REMARKS:

Table 5.4-5. EPRI LIME FGD SYSTEM DATA BOOK PRESATURATOR SPECIFICATIONS

CHECKED BY ______________ DATE ____________

COMPUTED BY ______________ DATE ____________

COMPANY ______________________________________ LOCATION ______________

SUPPLIER ____________________ P.O. NO. ______________ PRICE EACH $ __________

---

1 GENERAL DESCRIPTION

2 GAS FLOW: lb/h acfm AT °F

3 MATERIAL
ESTIMATED WEIGHT

4 INLET DIMENSIONS

5 OUTLET DIMENSIONS

6 L/G RATIO

7 COMPOSITION OF COOLING LIQUOR

8 SPRAY CONFIGURATION

9 SPRAY WASH, TYPE (STEAM, WATER, AIR)

10 GAS COMPOSITION: CO_2 O_2 H_2O SO_x NO_x
(% by weight)

11 PARTICULATE LOADING: gr/scf

12 WORKING PRESSURE: psig AT °F

13 MANHOLE GASKET MAT'L

14 PRESSURE DROP: IN. WG. ACROSS PRESATURATOR

In recent years, there has been a shift toward the use of mobile-bed absorbers (a modification of packed towers) and spray tower absorbers. (See Section 4.6 for a discussion of mobile-bed absorbers.) The following discussion focuses on these two configurations.

Several factors should be considered in the design of the absorber:

1. Pressure drop
2. Scaling and plugging
3. Corrosion/erosion

5.4.6.1 Pressure Drop--

A typical pressure drop in a spray tower is 2 in. H_2O, whereas in a mobile-bed absorber a pressure drop of 6 to 8 in. H_2O is typical. In a comparison based only on pressure drop, the spray tower is desirable. However, many other factors enter into the selection process.

A problem that may occur in mobile-bed absorbers is a phenomenon known as flooding. As the liquid rate increases, the pressure drop increases until the liquid actually begins to form a layer above the packing. This is known as a flood point. An important measure in avoiding flooding is to monitor inlet and outlet pressures continuously to identify a pressure drop higher than design with respect to gas flow rates.

5.4.6.2 Scaling and Plugging--

Spray towers have few internal components in the gas/liquid contact zone. They offer the potential for higher availabilities because of the lack of sites for deposition of solids. The accumulated solids provide sites for precipitation of dissolved mineral matter present in the coal and water sources. Under these deposits the chloride concentration grows, increasing the potential of stress-corrosion cracking of the metal surfaces.

Mobile-bed absorbers have the advantage of reducing scaling and plugging as a result of the motion of the mobile-bed material, usually polypropylene or rubber balls. However, solids may be deposited on the trays supporting the bed.

The use of a presaturator to cool flue gas to its adiabatic saturation temperature reduces the potential for scaling and corrosion at the slurry/gas (or wet/dry) interface areas of the absorber.

5.4.6.3 Erosion--

Absorber internals are subject to abrasion from the fly ash and recirculating solids inherent in a lime slurry system. To prevent erosion of the internals, 316 or 316 ELC stainless steel, rubber liners, and flaked-glass liners over carbon steel have been used. Configurations with liners may have problems associated with the proper application of the liners.

One additional area of potential erosion in absorbers is the spray nozzles. Refractory-type spray nozzles, such as those made of silicon carbide, are recommended to prevent erosion.

5.4.6.4 Corrosion--

The areas of most serious corrosion attack in the mobile-bed absorbers are the inlet to the absorber and above the mist eliminator. At the entrance to the absorbing region, hot gases may impinge on partially wetted surfaces and create wet/dry interfaces, thus making this the primary area of corrosion. The zone above the mist eliminator is often a stagnant area where residual particulate can accumulate and cause serious corrosion problems.

In spray towers, corrosion also attacks at the absorber inlet and above the mist eliminator. The stainless steel nozzles in a spray tower are subject to major corrosion attack when the recirculating slurry breaks down the corrosion resistant oxide film.

In absorbers having fiberglass-reinforced plastic (FRP) walls, abrasion attacks the outer protective layer of the coating and exposes the inner resin layer to chemical attack (corrosion). When this happens, the fiberglass mat begins to shred. The shredded areas can serve as sites for scale formation.

If this happens in a mobile-bed absorber, the shredded material collects on the top of the mobile-bed packing, increasing the pressure drop and the chances of flooding the tower. The risk of having more serious structural damage from corrosion may bring a decision to use other materials of construction.

If shredding occurs in a spray tower, the spray nozzles may plug; in systems containing pump screens, plugging of the screens may bring serious damage through pump cavitation.

Table 5.4-6 illustrates a typical specification to be completed by the utility, architect/engineer, or system supplier for the absorber vendor.

5.4.7 Absorber Recirculation Pumps

Some absorber systems are designed to recycle slurry directly from the bottom of an absorber vessel. However, most lime scrubbing systems incorporate a recirculation or recycle

Table 5.4-6. EPRI LIME FGD SYSTEM DATA BOOK ABSORBER SPECIFICATIONS

CHECKED BY ____________ DATE ________ SPEC. NO. ____________

COMPUTED BY ____________ DATE ________ PROJ. NO. ____________

COMPANY ______________________________ LOCATION ______________

EQUIPMENT NO. ____________ FOR USE ON ____________ TOTAL NO. REQ'D. ________

SUPPLIER ______________________ P.O. NO. ________ PRICE EACH $________

1	GENERAL DESCRIPTION
2	
3	FLOW DIAGRAM
	GENERAL INFORMATION
4	TYPE ABSORBER
5	DIAMETER HEIGHT MATERIAL IN TOWER
6	SPECIFICATIONS: FABRICATION TEST
7	WORKING PRESSURE: PSIG AT °F. DESIGN PRESSURE: PSIG AT °F.
8	TEST PRESSURE: PSIG WATER PSIG AIR
9	WIND LOAD SEISMIC LOAD
10	EST. WEIGHT LBS. EMPTY LBS. FILLED WITH WATER. CAPACITY GAL.
	SHELL SECTIONS
11	HEIGHT: RECYCLE TANK DEMISTER ABSORPTION SECTION
12	MAT'L. AND THICKNESS: BASE TOP INTERMED.
13	CORROSION ALLOWANCE SEAMS: WELDED BRAZED
14	TYPE OF FLANGE JOINT
15	DEMISTER: TYPE MATERIAL
	HEADS
16	TYPE BOLTED ON WELDED ON BRAZED ON
17	MAT'L. AND THICKNESS: BOTTOM TOP
18	CORROSION ALLOWANCE
	SUPPORT
19	TYPE HEIGHT MAT'L. AND THICKNESS
	NOZZLES
20	TYPE
	USE NUMBER SIZE LOCATION
21	GAS INLET
22	GAS OUTLET
23	LIQUID OUTLET
24	RECYCLE
25	LIQUID INLET
27	DIA. HOLES ON ROWS "APART
28	LEVEL CONTROL
29	GAUGE GLASS
30	MANOMETER
31	MANHOLE
32	GASKET MATERIAL TYPE OF PAINT
	TRAYS
33	NO. OF TRAYS SPACING DIAMETER
34	BUBBLE CAPS/SIEVES: NO. PER TRAY SIZE
35	RISERS: SIZE % RISER AREA MAT'L.
36	DOWNCOMERS: NO. AND SIZE TYPE MAT'L.
37	MATERIALS AND THICKNESS: TRAYS BUBBLE CAPS
38	PRESSURE DROP IN. WG. PER TRAY
	PACKING
39	TYPE AND SIZE: MATERIAL
40	WEIGHT OF PACKED SECTION WEIGHT FACTOR
41	PRESSURE DROP IN. WG. PER PACKED SECTION
42	PACKING SUPPORT MATERIAL
	SPRAY NOZZLES
43	NO. AND TYPE MATERIAL SIZE
44	ORIENTATION
45	PRESSURE DROP IN. WG. ACROSS THE ABSORBER
	PROCESS INFORMATION
46	GAS COMPOSITION(%): CO_2 O_2 H_2O SO_x NO_x
47	GAS FLOW: lb/hr, acfm AT °F
48	SO_2: lb/hr, SO_3: lb/hr
49	SO_x REMOVAL EFFICIENCY: REQ'D. DESIGN
50	LIQUID: lb/hr, SOLIDS: %, COMPOSITION(%):
51	LIQUID FLOW: RECIRCULATION GPM, BLEED GPM
52	LIQUID pH: RECIRCULATION BLEED

REMARKS AND SPECIAL DETAILS:

tank that receives the effluent by gravity from the absorber. The slurry is then pumped from these tanks. Whichever system is used, the design and specification of the pumps are identical. The major factors to be considered in recirculation pump design are as follows:

1. Corrosion
2. Erosion
3. Pump seals
4. Suction head
5. Maintenance simplicity

5.4.7.1 Corrosion--

Although the pH of the slurry in the reaction tank pump should be greater than 7, it may on occasion dip to 3 or 4. In those cases, erosion-resistant alloy pumps would be attacked. High grade alloy (e.g., Hastalloy) or rubber-lined pumps are therefore required for completely reliable corrosion resistance.

5.4.7.2 Erosion--

The abrasive nature of the slurry requires rubber-lined pumps or erosion-resistant alloy pumps; however, the corrosion potential eliminates erosion resistant alloy from consideration if, as stated, completely reliable service is the goal.

5.4.7.3 Pump Seals--

The pump must be packed with seal water to prevent erosion of the pump shaft from erosive particulate. Individually controlled seal water supplies should be used.

5.4.7.4 Suction Head--

The pump should have an NSPH greater than 10 ft to prevent outgassing. In addition to reducing the flow rate, the cavitation caused by outgassing can destroy the rubber lining in the pump.

Table 5.4-7a is a typical specification for a reaction tank pump as it would be completed by the utility, architect/engineer, or system supplier for the pump vendor.

5.4.7.5 Maintenance Simplicity--

Most manufacturers have designed pumps that are easy to maintain. Pumps should be placed so that these maintenance features can be best exploited. Table 5.4-7b is a typical specification for an absorber recirculation pump.

5.4.8 Absorber Recirculation Tank

The absorber recirculation tank holds absorber underflow and recirculates it to the absorber. Since fly ash may carry over from the fabric filter, precipitator, or venturi, the

Table 5.4-7a. EPRI LIME FGD SYSTEM DATA BOOK
REACTION TANK PUMP SPECIFICATIONS

COMPANY ____________________ LOCATION ____________________

EQUIPMENT NO. ____________ FOR USE ON ____________ TOTAL NO. REQUIRED ____________

SUPPLIER ____________________ P.O. NO. ____________ PRICE EACH $ ____________

GENERAL INFORMATION

TYPE ____________________

DUTY: CONTINUOUS ____________ INTERMITTENT ____________

SERVICE ____________________

PROCESS INFORMATION

LIQUID: ____________________

DESIGN FLOW: NORMAL ________ MAX ________ GPM

PUMPING TEMPERATURE ____________ °F

SP. GR. @ PUMPING TEMPERATURE ____________

VISCOSITY @ PUMPING TEMPERATURE ____________

VAPOR PRESS. @ PUMP TEMP. ____________ (FT.LIQ.)

PH VALUE ____________

CORROSIVE MATERIAL ____________

SOLIDS (MAX. DIA.) ____________

HYDRAULIC INFORMATION ________ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+) ____________

STATIC SUCTION LIFT (-): HEAD (+) ____________

SUCTION FRICTION HEAD (-) ____________

TOTAL SUCTION HEAD (17+18+19) ____________

STATIC DISCHARGE HEAD ____________

DISCHARGE FRICTION HEAD ____________

DISCHARGE PRESS. ABOVE LIQ. (ABS.) ____________

TOTAL DISCHARGE HEAD (21+22+23) ____________

TOTAL DYNAMIC HEAD (24-20) ____________

NPSH AVAILABLE (20-13) ____________

NPSH REQUIRED ____________

PUMP

MANUFACTURER ____________

RPM ____________

PERFORMANCE CURVE ____________

SERIAL NO. ____________

BPH @ SERVICE CONDITIONS

@ MAX. FLOW FOR IMPELLER ____________

ROTATION @ DRIVE SHAFT END ____________

COPIES REQUIRED OF: ____________

PERFORMANCE CURVES ____________

DIMENSION DRWGS. ____________

OPERATING AND MAINTENANCE INSTRUCTIONS ____________

MATERIALS

MATERIAL CODE - EXTERNAL CASING ____________ INTERNAL PARTS ____________

I - CAST IRON	INTERNALS CODE	I	B	S	C
B - BRONZE	IMPELLER	I	B	S	C
S - STEEL	INNER CASE PARTS	I	B	S	C
C - 11-13% CHROME	SLEEVE (PACKED)	Ch	Ch	Af	Af
A - ALLOY	SLEEVE (SEAL)	C	C	C	C
h - HARDENED	WEAR RINGS		B	Ch	Ch
f - FACED	SHAFT	S	S	S	S
	LANTERN RING				
	PACKING GLAND				

SUCTION CONN: SIZE ____________ POSITION ____________

DISCHARGE CONN: SIZE ____________ POSITION ____________

CONN. RATING ____________ TYPE ____________

PACKING TYPE ____________

LANTERN RINGS ____________ MATERIAL ____________

COOLING ____________

BEARINGS: TYPE ____________ GREASE ____________ OIL ____

IMPELLER: TYPE ________ SIZE FUR. ________ MAX. ________

VENT CONN: ____________ DRAIN CONN. ____________

FLUSHING CONNECTION: ____________

DRIVER ____________

FURNISHED WITH PUMP ____________ BY OTHERS ____________

TYPE: ____________

FRAME: ____________

MANUFACTURER: ____________

ENCLOSURE ____________

VOLTS ________ PHASE ________ CYCLE ____

HP ________ RPM ________

BEARINGS ____________ LUBRICATION ____________

COUPLING GUARD ____________

NOTES:

Table 5.4-7b. EPRI LIME FGD SYSTEM DATA BOOK ABSORBER RECIRCULATION PUMP SPECIFICATIONS

COMPANY ____ LOCATION ____

EQUIPMENT NO. ____ FOR USE ON ____ TOTAL NO. REQUIRED ____

SUPPLIER ____ P.O. NO. ____ PRICE EACH $ ____

GENERAL INFORMATION

TYPE ____

DUTY: CONTINUOUS ____ INTERMITTENT ____

SERVICE ____

PROCESS INFORMATION

LIQUID: ____

DESIGN FLOW: NORMAL ____ MAX ____ GPM

PUMPING TEMPERATURE ____ °F

SP. GR. @ PUMPING TEMPERATURE ____

VISCOSITY @ PUMPING TEMPERATURE ____

VAPOR PRESS. @ PUMP TEMP. ____ (FT.LIQ.)

PH VALUE ____

CORROSIVE MATERIAL ____

SOLIDS (MAX. DIA.) ____

HYDRAULIC INFORMATION ____ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+) ____

STATIC SUCTION LIFT (-): HEAD (+) ____

SUCTION FRICTION HEAD (-) ____

TOTAL SUCTION HEAD (17+18+19) ____

STATIC DISCHARGE HEAD ____

DISCHARGE FRICTION HEAD ____

DISCHARGE PRESS. ABOVE LIQ. (ABS.) ____

TOTAL DISCHARGE HEAD (21+22+23) ____

TOTAL DYNAMIC HEAD (24-20) ____

NPSH AVAILABLE (20-13) ____

NPSH REQUIRED ____

PUMP

MANUFACTURER ____

RPM ____

PERFORMANCE CURVE ____

SERIAL NO. ____

BPH @ SERVICE CONDITIONS

@ MAX. FLOW FOR IMPELLER ____

ROTATION @ DRIVE SHAFT END ____

COPIES REQUIRED OF: ____

PERFORMANCE CURVES ____

DIMENSION DRWGS. ____

OPERATING AND MAINTENANCE INSTRUCTIONS ____

MATERIALS

MATERIAL CODE - EXTERNAL CASING ____ INTERNAL PARTS ____

I - CAST IRON
B - BRONZE
S - STEEL
C - 11-13% CHROME
A - ALLOY
h - HARDENED
f - FACED

INTERNALS CODE	I	B	S	C
IMPELLER	I	B	S	C
INNER CASE PARTS	I	B	S	C
SLEEVE (PACKED)	Ch	Ch	Af	Af
SLEEVE (SEAL)	C	C	C	C
WEAR RINGS		B	Ch	Ch
SHAFT	S	S	S	S
LANTERN RING				
PACKING GLAND				

SUCTION CONN: SIZE ____ POSITION ____

DISCHARGE CONN: SIZE ____ POSITION ____

CONN. RATING ____ TYPE ____

PACKING TYPE ____

LANTERN RINGS ____ MATERIAL ____

COOLING ____

BEARINGS: TYPE ____ GREASE ____ OIL ____

IMPELLER: TYPE ____ SIZE FUR. ____ MAX. ____

VENT CONN: ____ DRAIN CONN. ____

FLUSHING CONNECTION: ____

DRIVER ____

FURNISHED WITH PUMP ____ BY OTHERS ____

TYPE: ____

FRAME: ____

MANUFACTURER: ____

ENCLOSURE ____

VOLTS ____ PHASE ____ CYCLE ____

HP ____ RPM ____

BEARINGS ____ LUBRICATION ____

COUPLING GUARD ____

NOTES:

absorber tank may contain fly ash in addition to lime, calcium sulfite, and calcium sulfate. The slurry should therefore be considered mildly abrasive. The pH in a properly controlled lime slurry tank should be 5.5 to 6.5; however, the pH can have excursions as low as 3. The primary factor to consider is corrosion/erosion.

5.4.8.1 Corrosion/Erosion--

The pH of the slurry in the recirculation tank should be at least 5.5. In a well-controlled system, coated carbon steel is probably adequate; pH excursions can occur, however, making stainless steel, rubber-lined carbon steel, and fiberglass coated steel the better alternatives.

Table 5.4-8 illustrates a typical specification to be completed by the utility, architect/engineer, or system supplier for the tank vendor.

5.4.9 Mist Eliminator

A mist eliminator is a device used to collect and return to the scrubbing liquor the slurry droplets entrained with the gas exiting the scrubber. A well-designed mist eliminator is needed to prevent corrosion and scaling of downstream equipment. It can also substantially reduce the reheat energy requirement, because there would be less water to vaporize.

Several types of mist eliminators are available. For lime scrubbing operations, however, the zigzag baffle configuration (chevron) is almost universally used. The design of a complete mist eliminator system is complex, because several conflicting objectives must be considered. The desire for high collection efficiency and for methods to reduce reentrainment must be weighed against washability and susceptibility to plugging. Associated factors to consider are the scrubber system design and operating conditions, system construction, scrubbing medium, solids content of the slurry, and sulfur content of the coal.

Bulk separators and knockout devices are used to remove most large liquid droplets from the gas before the stream passes through the mist eliminator. Special drainage features, such as hooks and pockets, have been applied to lime scrubbing systems.

For lime scrubbing systems, mist eliminator design specifies three- or four-pass, 90-degree bend, chevron mist eliminators with vanes made of reinforced plastic and spaced 1 to 3 in. apart. Mist eliminators are usually housed atop the absorber and placed 4 to 20 ft above the last absorbing stage. Superficial gas velocities range from 7.5 to 21.5 ft/s.

Table 5.4-8. EPRI LIME FGD SYSTEM DATA BOOK
ABSORBER RECIRCULATION TANK SPECIFICATIONS

Sheet of

REV

CUSTOMER ______________________

PLANT LOCATION ______________________

SERVICE ______________________

JOB NO. ______________________

EQUIPT. NO. ______________________

FILE NO. ______________________

P.O. NO. ______________________

Type of Tank ______________________

Size: ________ Diam. ________ Height ________ Capacity ________

GENERAL NOTES

1) For required capacity as shown, Mfg. to advise diameter and height of tank for the most economical utilization of plate.
2) Nozzle orientation to be furnished later.
3) Nozzle location and design tube furnished later with mechanical design.
4) Ladder Clips & Ladder:
   ________ Inside ________ Outside
5) Design P. ________ Design T ________
6) Paint ______________________
7) Lining - Fiberglass or rubber Note 1

NOZZLES	MARK	NO.	SIZE	RATING
Inlet				
Outlet				
Drawoff Elbow				
P & V Vent				
Level Gage				
Thermowell				
Roof Manhole				
Shell Manhole				

DESIGN DATA

Tank Material Min. Plate Thick SP GR

Corrosion Allowance: Shell in.; Bottom in.; Roof in.

APPURTENANCES (BY)

Level Gage or Gate Column: Yes No Type

Make Fig. or Equal Float

Pressure & Vacuum Vent Valve: Yes No Pressure oz.

Make Fig. or Equal Vacuum oz.

Gage Hatch: Yes No. Make Fig. or Equal

Thermometer Well: Yes No Length In

Make Model or Equal Material

Thermometer: Yes No Stem Length In

Make Model or Equal Range

REMARKS:

The following recommendations should be considered in mist eliminator design for lime scrubbing systems:

- The continuous chevron is better than the noncontinuous because of its greater strength and relatively lower cost.
- Blade spacings between 1.5 and 3.0 in. are desirable.
- On vertical units, special features such as hooks and pockets can be used to decrease reentrainment.
- Bulk separation and knockout devices are desirable, because they yield increased removal efficiency and greater design flexibility.
- Wash systems using blended water, consisting of pond return water or thickener overflow and freshwater, are recommended. Intermittent high-pressure, high-velocity wash systems are preferred to continuous wash systems because of impact on water usage and closed-loop operation.

Table 5.4-9 illustrates a few typical specifications for a mist eliminator system.

5.4.10 Soot Blowers

The soot blowers described in this section have the function of removing deposits occurring in duct work downstream of the absorber. These deposits consist of fine fly ash particles and condensed acids. Choice of the soot blower cleaning medium (compressed air or steam) is determined by economic considerations, since compressed air and steam offer comparable service. If the proposed plant is located in an arid region or if service water is expensive, compressed air would be more economical. In general, however, maintenance costs are higher for steam blowing.

The compressed air requirements for soot blowing are cyclic in nature. Thus, air compressors must be designed to respond efficiently to varying airflow demands. The extent of these variations would determine the best compressor control from the three types most commonly used: constant pressure, pressure differential, and automatic dual. Systems with properly sized compressors can keep pace with soot blower air requirements and maintain a stable header pressure. An operating condition that can cause a momentary pressure drop in the header is the frequent loading and unloading of the compressor and simultaneous releasing of blower valves. This condition can be taken into account in the design of the air piping system (increase the pipe diameter) or the control circuit (include a time delay to override the low-pressure switch in the header).

Table 5.4-9. EPRI LIME FGD SYSTEMS DATA BOOK

MIST ELIMINATOR

1. Type: continuous chevron
2. Shape: Z-shaped
3. Number of passes: four
4. Vane spacing: 1 to 3 in.
5. Number of stages: one
6. Freeboard distance: 4 to 6 ft
7. Superficial gas velocity: 9 to 14 ft/s
8. Material of construction: FRP
9. Wash duration: intermittent high velocity
10. Wash water pressure: 30 to 50 psig
11. Features recommended: a) hooks and pockets and b) bulk separation and knockout devices

Mechanical design integrity is an important consideration in compressor selection. For long-term durability of the gear train, the manufacturer must exceed the requirements of the American Gear Manufacturers Association (AGMA standard 921.06) in terms of the actual gearing service factor applied to each stage of compression. Internal air passages of the compressor must be lined with corrosion resistant material; critical components, such as impellers, should be made of stainless steel. The interstage air coolers must be made of nonferrous materials if the compressor is subjected to a corrosive atmosphere. The compressor should be designed so that internal components are accessible for maintenance.

Table 5.4-10 is a typical specification to be completed by the utility, architect/engineer, or equipment supplier for the centrifugal compressor vendor.

5.4.11 Stack Gas Reheater

Stack gas reheat may be necessary for the following reasons:

1. Prevention of downstream condensation and subsequent corrosion.
2. Reduction or elimination of plume visibility.
3. Enhancement of plume rise and pollutant dispersion.

Several methods are available for reheating the saturated flue gases exiting from the absorber.

5.4.11.1 In-line Reheat--

This system consists of tube banks arranged perpendicularly to the gas flow. Steam or hot water flows through the tubes, imparting the required amount of temperature increase.

5.4.11.2 Direct-fired Reheat--

An in-line burner is installed in which a clean fuel (No. 2 oil or gas) is fired. The flue gas is thereby heated to the required temperature. In a direct-fired reheat design, combustion should occur in a separate chamber and not in the duct work. This assures the integrity of the flame. A number of systems had trouble keeping a flame when the burners were located in the duct work.

5.4.11.3 Indirect Reheat--

Ambient air is heated either in a combustion chamber or through a heat exchanger and then mixed with the flue gas. The system thus avoids the plugging and corrosion problems that come from particulate and acid mist in the flue gas.

Table 5.4-10. EPRI LIME FGD SYSTEM DATA BOOK
CENTRIFUGAL COMPRESSOR SPECIFICATIONS

CHECKED BY ______ DATE ______ SPEC. NO. ____________
COMPUTED BY ______ DATE ______ PROJ. NO. ____________
COMPANY ____________________ LOCATION ____________________
EQUIPMENT NO. ____________ FOR USE ON ____________ TOTAL NO. REQ'D. ____________
SUPPLIER ____________ P.O. NO. ____________ PRICE EACH $ ____________

	GENERAL INFORMATION		CONSTRUCTION
1	TYPE	33	IMPELLER: SIZE TYPE
2		34	NO. STAGES RPM
3		35	SUCT. CONN. TYPE
4	DUTY: CONTINUOUS ☐ INTERMITTENT ☐	36	DISCH. CONN. TYPE
5	SERVICE	37	CONN. RATING
6		38	SHAFT SEAL
7		39	ROTATION
	PROCESS INFORMATION	40	BEARINGS
8	GAS, NAME & COMPOSITION:	41	LUBRICATION COOLING
9		42	MATERIALS: CASE
10		43	IMPELLER
11	CONDITION OF GAS: WET, DRY, SOLIDS, CORROS.	44	SHAFT
12		45	SEALS
13	MOL. WEIGHT SP. GR. @ 70°F.	46	MOUNTING BASE
14	SP. GR. @ SUCTION FLOW TEMP.	47	
15	SP. HT., CP. CP/CV		ACCESSORIES
16	CRITICAL TEMP. °F. CRITICAL PRESS, PSIA	48	INTERCOOLER
17	SUCT. TEMP. °F. SUCTION PRESS, PSIA	49	
18	VOL. FLOW @ SUCT. NORMAL, CFM	50	AFTERCOOLER
19	VOL. FLOW @ SUCT. MAX. REQ'D., CFM	51	
20	VOL. FLOW @ SUCT. DESIGN, CFM	52	RECEIVER
21	WEIGHT FLOW, DESIGN, LBS./MIN.	53	REGULATION: CONST. PRES. ☐ CONST. VOL. ☐
22	DISCH. PRESS, PSIA, NORMAL. MAX.	54	ADJ. INLET VALVE ☐ STABLE LIMIT CONTROL ☐
23	DISCH. TEMP. °F.	55	
24	HT. CONTENT OF GAS, BTU/CU. FT.	56	INLET FILTER
25	COOLING WATER: PRESS, PSIG TEMP. °F.		DRIVER
26	THEORETICAL HP MAX. BHP	57	FURNISHED WITH COMPRESSOR ☐ BY OTHERS ☐
27	VOL. EFF. MECH. EFF.	58	TYPE & MAKE
28	ATM. PRESS, PSIA	59	
29		60	
30		61	VOLTS PHASE CYCLE HP RPM
31	PERFORMANCE CURVES YES ☐ NO ☐	62	
32		63	COUPLING TYPE

REMARKS -

5.4.11.4 Bypass Reheat--

A portion of flue gas, having been treated for fly ash removal, is bypassed and mixed with the gas at the scrubber exit. This method may not apply to systems where regulations require 90+ percent SO_2 removal efficiency. (A minimum of 10 percent of the flue gas is needed to provide adequate reheat. Therefore, the FGD system would have to remove virtually all of the inlet SO_2 to achieve overall removal of 90 percent.) In addition, Federal New Source Performance Standards (NSPS) currently being considered may eliminate this option.

The following are general recommendations for reheat systems, regardless of the chosen strategy:

- Soot blowers should be installed on in-line reheaters.
- An efficient mist eliminator should be installed to decrease the load on the reheat system.
- Gas should be heated by 25° to 50°F to prevent downstream water condensation.

The following are general specifications for the stack gas reheating system.

1. Design temperature increment: 50°F.
2. Preferred type: in-line reheater.
3. Heating medium: steam.
4. Material of construction: 316L SS.
5. Recommended feature: installation of soot blowers.

The trend in reheat strategies, as evidenced by FGD systems scheduled for immediate and future operation, is away from in-line and direct combustion methods and toward indirect hot air reheat. The rationale for this trend is the problems encountered in the former and the need for oil or natural gas in the latter.

In-line reheat systems have been subject to corrosion and plugging in the tubes. The corrosion in many cases has been so severe that even the heartier alloy listed above has been unsatisfactory under some operating conditions. A number of the major system suppliers still recommend in-line reheaters, especially when parasitic energy demand must be minimized. The corrosion of high-alloy materials is attributed to stress corrosion caused by chloride, whereas carbon steel is more susceptible to acid corrosion caused by high sulfur dioxide concentrations. If low sulfur/low chloride, low sulfur/high chloride, or high sulfur/low chloride environments can be identified, in-line reheaters may be successfully used. Many of these problems have been attributed to inefficiency of the upstream mist eliminator and inadequate self-cleaning techniques (soot blowers).

5.4.12 Dampers

Isolation dampers are used in a coal-fired power plant to prevent the flow of the gas into the FGD system. The purposes of isolation are to continue boiler operations while the absorber modules are under maintenance and to take a scrubber module off-line during reduced load. The common damper designs include the slide gate (guillotine) style, the single-blade butterfly style, and the multiblade parallel (louvre) style.

The current trend is toward two-stage louvre dampers with a pressurized seal air system to maintain positive pressure between them. This pressurized seal air system increases the parasitic energy demand by the FGD system, but significantly improves damper operation.

Operating conditions that must be provided to the damper manufacturer are: maximum temperatures for gas stream operation and design, gas stream pressure, and gas stream analysis. The damper frames are usually channel-type, of either rolled or formed plate. The material and weight of the frames should be determined on the basis of stress due to seismic loading, total damper size and weight, and operating conditions. The blade deflection should be less than 1/360 of the blade span. A detailed stress analysis should be performed on the blade for a specific design. Each damper requires an activator that should be mounted on it out of the gas stream.

In specifying dampers, care must be taken to minimize areas of fly ash deposition. In the past, these areas have caused corrosion problems as well as rough working of the damper mechanisms. Proper selection of materials of construction and adequate mechanical design are necessary to assure reliable operation of isolation dampers.

Table 5.4-11 is a typical specification to be completed by the utility, architect/engineer, or equipment supplier for the dampers.

5.4.13 Duct Work

The duct work is the passage that transports flue gas from the boiler outlet through the particulate control equipment and the absorber to the stack. Because the design procedure for duct work is well standardized, only some basic features are described here.

The duct work upstream from the absorber is usually made of 3/16- to 1/4-in. mild steel plates welded in a rectangular cross section. The length and width are about equal. The duct work is supported by angle frames, which are stiffened at uniform

Table 5.4-11. EPRI LIME FGD SYSTEM DATA BOOK
DAMPER SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO. ____________
COMPUTED BY ________ DATE ________ PROJ. NO. ____________
COMPANY ______________________________ LOCATION ____________
EQUIPMENT NO. ______________ FOR USE ON __________ TOTAL NO. REQ'D ______
SUPPLIER ______________ P.O. NO. __________ PRICE EACH $__________

1 GENERAL DESCRIPTION
2
DESIGN CONDITIONS
3 GAS FLOW: ACFM, MAX AT °F, MAX
4 GAS COMPOSITION(%): MAX
5 MAX. PRESSURE: IN. WG., MAX. LOSS IN. WG. ACROSS FULL OPEN BLADE
6 MAX. LEAKAGE: TO SYSTEM ACFM, TO AMOUNT ACFM
TEST INFORMATION
7 PRESSURE TEST: PSIG WATER PSIG AIR
8 WIND LOAD SEISMIC LOAD
9 LEAKAGE TEST
10 DEFLECTION TEST MAX. DEFLECTION OF BLADE SPAN
WELDING
11 SECTION OF BOILER CODE
12 DYE PENETRANT TEST
BLADES
13 MATERIAL THICKNESS TYPE
ACTIVATOR
14 TYPE DRIVE
BEARINGS
15 TYPE MATERIAL SIZE
DAMPER
16 TYPE LEAKAGE ACFM PRESSURE LOSS IN. WG.
SPECIAL INSTRUCTIONS:

intervals. The ducting downstream of the absorber and to the reheater should be lined with or constructed of corrosion resistant material to combat the wet, acidic environment.

Expansion joints are an essential part of the duct work because of their ability to absorb thermal movements, vibrations, and limiting forces on equipment. Expansion joints designed to compensate for axial movements are suitable in utility applications. The joints must be resistant to erosion and corrosion. They normally operate with a residual stress pattern that amplifies stress corrosion problems. Because of this situation, condensation in expansion joints during shutdowns may attack the metal. Expansion joints cannot be designed with a corrosion allowance because even a small allowance will materially limit the movement capability of a joint. Type 321 stainless steel is resistant to stress corrosion over a wide range of temperatures. Any application of this type of expansion joint above 800°F may subject it to carbide precipitation and subsequent intergranular attacks. Therefore, care should be taken to prevent major temperature excursions in the duct work after a reheater. Expansion joints in the utility industry should be equipped with a replaceable liner to reduce erosion by particulate matter.

Table 5.4-12 is a preliminary data sheet for duct work and expansion joints.

5.4.14 Booster Fan

To overcome the pressure drop in a scrubbing system, fans are used to push or pull the gas through the system. This FGD system pressure drop may be overcome by the main boiler fan or by a control system booster fan.

Although wet booster fans have a size advantage as a result of the wet gas being cooler and having less volume, the trend has been to dry (high volume), forced draft (FD) fans. A dry fan is defined as one that does not see a saturated gas and is not sprayed with wash water. Normally a dry fan is located upstream of the absorber or downstream of the reheater. Because of abrasion effects of particulate matter in a gas stream, a dry fan should only be placed before a scrubber absorber if there is a particulate removal device upstream from it. Factors that should be considered in the specification of a dry fan are as follows:

1. Corrosion
2. Cleaning and inspection
3. Temperature rise

Table 5.4-12. EPRI LIME FGD SYSTEM DATA BOOK
DUCT WORK SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO. __________

COMPUTED BY ________ DATE ________ PROJ. NO. __________

COMPANY ________________________ LOCATION ____________

EQUIPMENT NO. ______________ FOR USE ON ________ TOTAL NO. REQ'D ______

SUPPLIER ________________ P.O. NO. __________ PRICE EACH $________

1 GENERAL DESCRIPTION
2
3

OPERATING CONDITIONS

4 GAS FLOW: ACFM AT °F, MAX
5 STATIC PRESSURE IN. WG.
6 GAS COMPOSITION

UPSTREAM DUCTWORK

7 GAS VELOCITY FPS AT °F, LENGTH FT, WIDTH FT
8 MATERIAL THICKNESS
9 WELD: TYPE TEST
10 SUPPORTS: TYPE SPACING NOS.

DOWNSTREAM DUCTWORK

11 GAS VELOCITY FPS AT °F, LENGTH FT, WIDTH FT
12 MATERIAL , THICKNESS in.
13 WELD: TYPE , TEST
14 SUPPORTS: TYPE SPACING NB
15 LINING: MATERIAL THICKNESS in.

EXPANSION JOINTS

16 TYPE NOS. LOCATIONS
17 MATERIAL LINER
18 SIZE
19 MOVEMENTS: in. AXIAL in. LATERAL

SPECIAL INSTRUCTIONS:

5.4.14.1 Corrosion--

Although fly ash and corrosive gases are handled by the dry fans, carbon steel is an adequate material of construction for forced draft fans. With proper mist elimination and reheat, scrubber solids that can cause deposition, corrosion, and imbalance should not appear on induced draft fans.

5.4.14.2 Cleaning and Inspection--

All fans should have adequate cleanout doors. This is especially important on induced draft dry fans. Inspection ports are also useful to determine if deposits are accumulating.

5.4.14.3 Temperature Rise--

The flue gas temperature rises slightly (10°F) as it absorbs the compressive energy of the fan. Reheat temperatures and duct work velocities should be designed for this.

In view of the poor performance record of wet fans, their specification should be accompanied with a rationale for circumventing known problems of erosion, corrosion, and solids deposition.

Table 5.4-13 is a typical specification to be completed by the utility, architect/engineer, or equipment supplier for the fan vendor.

5.4.15 Lime Silos

The following factors are important in specifying a lime storage silo:

1. Materials of construction
2. Conveying systems
3. Closed construction

5.4.15.1 Materials of Construction--

Cylindrical, unlined, carbon steel tanks with cone bottoms, or concrete silos can be used for lime storage. Concrete silos must be cured for several months before use.

5.4.15.2 Conveying Systems--

Either pneumatic or mechanical conveying systems are used to move lime. Pneumatic systems are more common and offer easier maintenance, but they allow water vapor into the system if not operated closed loop. Larger fabric filters are required for pneumatically conveyed silos than for mechanically conveyed silos.

5.4.15.3 Closed Construction--

Any lime silo or transfer hopper must be closed to prevent the entry of water and to minimize absorption of water vapor and carbon dioxide.

Table 5.4-13. EPRI LIME FGD SYSTEM DATA BOOK
BOOSTER FAN SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO. ________

COMPUTED BY ________ DATE ________ PROJ. NO. ________

COMPANY ________________ LOCATION ________________

EQUIPMENT NO. ________ FOR USE ON ________ TOTAL NO. REQ'D. ________

SUPPLIER ________ P.O. NO. ________ PRICE EACH $ ________

	GENERAL INFORMATION		**CONSTRUCTION**
1	TYPE:	19	NON-SPARKING ☐
2	MFR.	20	WHEEL DIAMETER: INCHES
3	MODEL:	21	WHEEL MATERIAL:
4	DUTY: CONTINUOUS ☐ INTERMITTENT ☐	22	COATING OR LINING:
5	SERVICE:	23	SINGLE INLET ☐ DOUBLE INLET ☐
6		24	VARIABLE DAMPER ☐ INLET ☐ OUTLET ☐
7		25	SCREENED ☐ INLET ☐ OUTLET ☐
	PROCESS INFORMATION	26	HOUSING MAT'L.
8	AIR ☐ FUMES ☐ GAS ☐ VAPOR ☐	27	COATING OR LINING:
9	COMPOSITION:	28	HOUSING CLEANOUT ☐ DRAIN ☐
10		29	SHAFT MAT'L.
11		30	SHAFT DIAMETER
12	EXPLOSIVE ☐ NON-EXPLOSIVE ☐	31	BEARING MAKE & TYPE:
13	CORROSIVE ☐ NON-CORROSIVE ☐	32	
14	OPERATING TEMP. °F	33	EXTERIOR FINISH:
15	DISCHARGE CFM	34	
16	STATIC PRESSURE INCHES H_2O	35	
17	OUTLET VELOCITY FPM	36	
18		37	
	ORIENTATION		**DRIVE**
		38	FURN. WITH BLOWER ☐ OTHER ☐
		39	BELT ☐ VEE ☐ FLAT ☐
		40	DIRECT ☐ OTHER ☐
		41	BLOWER RPM:
		42	MOTOR MAKE:
		43	MOTOR TYPE:
		44	MOTOR FRAME:
		45	MOTOR HP RPM
		46	VOLTS CYCLES PHASE
		47	BASE:
		48	
		49	
NOTES -			

5.4.16 Lime Feeder

The lime feeder controls the amount of lime going into the slaker. If the lime slurry preparation system is controlled by varying the lime feed as the SO_2 inlet concentration varies (feed forward), then quantitative feeders are required. If an "on-off" slaker operation based on a control level in the lime storage stabilization tank is used, then volumetric feeders are adequate. If the quantity of lime used in the system must be accurately measured for accounting purposes, gravimetric meters will be needed. In many cases, the gravimetric feeder has little additional cost. In addition to feeder types, the following factors are important:

1. Conveying mechanism
2. System shutdown

5.4.16.1 Conveying Mechanism--

Belt conveyors, screw conveyors, oscillating hoppers, and vibrating hoppers are conveying methods used in lime feeding systems. The most common systems are the belt conveyor and the screw conveyor. The latter is best used for small- and medium-sized systems that operate continuously, since intermittent operation causes plugging when rising slaker moisture reacts with the lime. There are no major disadvantages of the belt feeder.

5.4.16.2 System Shutdown--

When the feeder system is stopped, steam and water vapor from the slaker rise and react with the lime. Care must be taken with all types of feeders to minimize this effect through proper ventilation of the slakers. In severe cases, even belt feeders could be plugged. Table 5.4-14 illustrates a typical conveyor specification as it would be prepared by a utility, architect/engineer, or system supplier for the conveyor vendor.

5.4.17 Lime Slaker

The lime slaker is needed to produce a consistent absorbent to remove the sulfur dioxide in the absorber. Since the properties of slaked lime affect the removal efficiency and economics of the system, the design of the slaker is important to the successful operation of a scrubbing system. The following factors should be considered in the design of a slaker:

1. Lime type
2. Slaker type
3. System reliability

Table 5.4-14. EPRI LIME FGD SYSTEM DATA BOOK
BELT CONVEYOR SPECIFICATIONS

SHEET 1 OF ______
SPEC. NO. ______
PROJ. NO. ______

CHECKED BY ______ DATE ______
COMPUTED BY ______ DATE ______
COMPANY ______ LOCATION ______
EQUIPMENT NO. ______ FOR USE ON ______ TOTAL NO. REQ'D. ______
SUPPLIER ______ P.O. NO. ______ PRICE EACH $ ______

	DUTY		ACCESSORIES
1	CONVEYOR LGTH. LIFT	20	SKIRTBOARDS: LGTH.
2	TPH: AVE. SURGE DESIGN	21	WALKWAY: WIDTH TYPE
3	HOW LOADED:	22	DECKING HANDRAILS
4	ANGLE TO DIRECTION OF BELT TRAVEL	23	COVER (TYPE)
5	HOURS/DAY	24	
6	NO. OF LOADING PTS.	25	
7	INSTALLATION: OUTDOOR ☐ INDOOR ☐	26	GUARD
8	OPERATION: CONTINUOUS ☐ INTERM'T. ☐	27	HOLDBACK: BAND, RATCHET
	FEED DESCRIPTION	28	HOLDBACK LOCATION
9	NAME	29	
10	DENSITY LB./CU. FT.	30	STRINGERS: WIRE ROPE, CHANNEL
11	MOISTURE	31	TRUSS, DECKPLATE
12	TEMP. °F. LUMPS °F. FINES °F.	32	BELT WIPER: BRUSH, WIRE, SPRAY
13	SIZE:	33	BLADE (SINGLE, DUPLEX, QUAD.)
14	MAX. LUMP % OF FEED	34	TAKE-UP: TRAVEL
15	CHARACTERISTICS:	35	SCREW, GRAVITY, SPRING
16	STICKY	36	VERTICAL, HORIZONTAL
17	CORROSIVE	37	DRIVE: V-BELT, CHAIN, SHAFT-MOUNTED
18	ABRASIVE	38	MOTOR TYPE:
19	ANGLE OF REPOSE	39	HP RPM V. PH. CY.

	DESCRIPTION							
40	BELT: WIDTH LGTH. SPEED IN F.P.M.					______ PLY ______ X ______ COVERS		
41	MAT'L. GRADE FINISH					OZ.		
42	BREAKER STRIP: YES ☐ NO ☐ TYPE OF SPLICE							
43	IDLER: TYPE	TROUGHERS	RETURNS	IMPACTS	TROUGH TRAINERS	RETURN TRAINERS		
44	DIA.							
45	SPACING							
46	BEARING							
47	LUBE.							
48	PULLEY: TYPE	HEAD	TAIL	SNUB	BEND	TAKE-UP		
49	MAT'L.							
50	DIA.							
51	LGTH.							
52	CROWN							
53	LAGGING							
54	HUBS							
55	BRGS.							

5.4.17.1 Lime Type--

Lime varies significantly with respect to the ease with which it is slaked. Magnesium limes require longer slaking times than some high-calcium limes. Extended slaking times can reduce the capacity of a 4-ton slaker to a 3-ton slaker. Therefore, slaking tests on the lime supply should be made before specifying the slaker. Since the number of slakers and the type can be influenced by the lime properties, the type of lime used should be carefully evaluated.

5.4.17.2 Slaker Type--

Two types of slakers are available for lime slurry operations: paste or detention. The detention slaker offers the following advantages: unrestricted size, more economical, flexibility with respect to lime quality, simplicity, capability of handling larger lime size, and natural draft ventilation. However, the paste slaker uses less water and produces smaller particle sizes in the slaked lime.

5.4.17.3 System Reliability--

Paste slakers, which are limited to 4 tons per hour of throughput, are an advantage to system reliability. Since more slakers are needed in large systems, slaker malfunctions do not severely affect the lime supply. Overall system reliability is improved.

5.4.17.4 Miscellaneous--

The slaking system should be located as close to the scrubber system as possible. A maximum 200-ft pumping distance is recommended for lime slurry feed. In order to maintain water balance, slurry lines should not be washed out when shut down, but rather blown out with air.

Table 5.4-15 illustrates a typical specification as it would be prepared by the utility, architect/engineer, or system supplier for the lime slaker vendor.

5.4.18 Lime Stabilization/Storage Tank

This tank serves the dual purpose of storing slaked lime for the scrubbing modules and allowing it to stabilize before pumping. The stabilization portion of the tank must be so sized that it has a retention time of at least 15 minutes. The balance of the tank is designed to hold a 6- to 12-hour supply of slaked lime. The partition between the two chambers is designed to prevent short-circuiting of the stabilizing lime.

Erosion is not a problem in lime slurry storage tanks. The hydrated lime forms a protective coating on the walls of the tank, which prevents erosion. Lime slurry tanks should not be acid cleaned, since this destroys the protective lime coating.

Table 5.4-15. EPRI LIME FGD SYSTEMS DATA BOOK SLAKER SPECIFICATIONS

CHECKED BY __________ DATE __________ SPEC. NO. __________
COMPUTED BY __________ DATE __________ PROJ. NO. __________
COMPANY __________ LOCATION __________
EQUIPMENT NO. __________ FOR USE ON __________ TOTAL NO. REQ'D. __________
SUPPLIER __________ P.O. NO. __________ PRICE EACH $__________

1	GENERAL DESCRIPTION
2	
3	
	PROCESS INFORMATION
4	LIME COMPOSITION(%): CaO , MgO , $CaCO_3$
5	LIME REACTIVITY: RESIDENCE TIME REQ'D. MIN
6	HEAT EVOLVED: BTU/LB LIME
7	FRESH WATER: pH; GPM; °F
8	RECLAIMED WATER: pH; GPM; °F
9	LIME FEEDER: TYPE , FEEDRATE LB/HR AT °F
10	SLURRY REQ'D.: LB/HR, pH, °F, % SOLIDS
	SLAKER
11	SIZE:
12	MATL. THK.
13	LINING MATL. THK.
	BAFFLES
14	TYPE: NO.
15	MATL. THK.
	AGITATOR
16	TYPE: SIZE:
17	MATL: THK.
	MOTOR
18	PHASE, RPM VOLTS
	DRIVE
19	TYPE: MATL.
	FABRICATION
20	WELD: TYPE , TEST

SPECIAL INSTRUCTIONS:

The tank should be covered to reduce the absorption of CO_2 from the air, and it should be vented to allow water vapor to leave. The height of the tank should be designed to provide sufficient NPSH for the lime slurry feed pumps.

Table 5.4-16 is a typical specification as it would be completed by the utility, architect/engineer, or system supplier for the tank vendor.

5.4.19 Lime Slurry Feed Pump

The lime slurry pumps supply slaked and diluted lime slurry to the absorber or absorption recirculation pumps. Factors that should be considered in the lime slurry pumps are as follows:

1. Abrasion
2. Pump seals
3. Lime slurry feed control

5.4.19.1 Abrasion--

Lime slurry would not be erosive if it did not contain grit and unreacted limestone cores; however, since these materials are present, erosion resistance must be provided.

Cast iron, erosion resistant alloy, and rubber-lined pumps are common in lime slurry supply systems. Some designers prefer to use rubber-lined pumps for single manufacturer consistency through the plant. Rubber-lined pumps are not required for corrosion prevention because low pH in the lime slurry feed should not occur.

5.4.19.2 Pump Seals--

The abrasive nature of the slurry requires pumps with seal water. Each seal water supply should be independently regulated to ensure uniform flow through the packing gland.

5.4.19.3 Lime Slurry Feed Control--

The lime slurry supply rate can be regulated by: varying the speed on the pump, letting the slurry slip in the pump as the control flow changes, or using a fresh slurry pump system that recycles the lime slurry in a loop and returns the excess to the lime slurry tank. The last technique is the preferred method since it prevents excessive wear on the lime slurry pumps and brings an adequate supply to the absorption train. Careful selection of the control valve is critical to minimize erosion/corrosion.

Table 5.4-17 is a typical specification as it would be completed by the utility, architect/engineer, or system supplier for the lime slurry pump vendor.

Table 5.4-16. EPRI LIME FGD SYSTEM DATA BOOK LIME STABILIZATION/STORAGE TANK SPECIFICATIONS

Sheet ____ of ____ REV

CUSTOMER ____________________ JOB NO. ____________________
PLANT LOCATION ____________________ EQUIPT. NO. ____________________
SERVICE ____________________ FILE NO. ____________________
____________________ P.O. NO. ____________________
Type of Tank ____________________
Size: ________ Diam. ________ Height ________ Capacity ________

GENERAL NOTES

1) For required capacity as shown, Mfg. to advise diameter and height of tank for the most economical utilization of plate.
2) Nozzle orientation to be furnished later.
3) Nozzle location and design tube furnished later with mechanical design.
4) Ladder Clips & Ladder:
   ________ Inside ________ Outside
5) Design P.________ Design T________
6) Paint ____________________
7) Lining - Fiberglass or rubber Note 1

NOZZLES	MARK	NO.	SIZE	RATING
Inlet				
Outlet				
Drawoff Elbow				
P & V Vent				
Level Gage				
Thermowell				
Roof Manhole				
Shell Manhole				

DESIGN DATA

Tank Material ________ Min. Plate Thick ________ SP GR ________
Corrosion Allowance: Shell ________ in.; Bottom ________ in.; Roof ________ in.

APPURTENANCES (BY ________)

Level Gage or Gate Column: Yes No Type ________
Make ________ Fig. ________ or Equal Float ________
Pressure & Vacuum Vent Valve: Yes No Pressure ________ oz.
Make ________ Fig. ________ or Equal Vacuum ________ oz.
Gage Hatch: Yes No. Make ________ Fig. ________ or Equal
Thermometer Well: Yes No Length ________ In
Make ________ Model ________ or Equal Material ________
Thermometer: Yes No Stem Length ________ In
Make ________ Model ________ or Equal Range ________

REMARKS:

Table 5.4-17. EPRI LIME FGD SYSTEM DATA BOOK
LIME SLURRY PUMP SPECIFICATIONS

COMPANY ____ LOCATION ____

EQUIPMENT NO. ____ FOR USE ON ____ TOTAL NO. REQUIRED ____

SUPPLIER ____ P.O. NO. ____ PRICE EACH $ ____

GENERAL INFORMATION

TYPE ____

DUTY: CONTINUOUS ____ INTERMITTENT ____

SERVICE ____

PROCESS INFORMATION

LIQUID: ____

DESIGN FLOW: NORMAL ____ MAX ____ GPM

PUMPING TEMPERATURE ____ °F

SP. GR. @ PUMPING TEMPERATURE ____

VISCOSITY @ PUMPING TEMPERATURE ____

VAPOR PRESS. @ PUMP TEMP. ____ (FT.LIQ.)

PH VALUE ____

CORROSIVE MATERIAL ____

SOLIDS (MAX. DIA.) ____

HYDRAULIC INFORMATION ____ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+) ____

STATIC SUCTION LIFT (-): HEAD (+) ____

SUCTION FRICTION HEAD (-) ____

TOTAL SUCTION HEAD (17+18+19) ____

STATIC DISCHARGE HEAD ____

DISCHARGE FRICTION HEAD ____

DISCHARGE PRESS. ABOVE LIQ. (ABS.) ____

TOTAL DISCHARGE HEAD (21+22+23) ____

TOTAL DYNAMIC HEAD (24-20) ____

NPSH AVAILABLE (20-13) ____

NPSH REQUIRED ____

PUMP

MANUFACTURER ____

RPM ____

PERFORMANCE CURVE ____

SERIAL NO. ____

BPH @ SERVICE CONDITIONS ____

@ MAX. FLOW FOR IMPELLER ____

ROTATION @ DRIVE SHAFT END ____

COPIES REQUIRED OF: ____

PERFORMANCE CURVES ____

DIMENSION DRWGS. ____

OPERATING AND MAINTENANCE INSTRUCTIONS ____

MATERIALS

MATERIAL CODE - EXTERNAL CASING ____ INTERNAL PARTS ____

I - CAST IRON	INTERNALS CODE	I	B	S	C
B - BRONZE	IMPELLER	I	B	S	C
S - STEEL	INNER CASE PARTS	I	B	S	C
C - 11-13% CHROME	SLEEVE (PACKED)	Ch	Ch	Af	Af
A - ALLOY	SLEEVE (SEAL)	C	C	C	C
h - HARDENED	WEAR RINGS		B	Ch	Ch
f - FACED	SHAFT	S	S	S	S
	LANTERN RING				
	PACKING GLAND				

SUCTION CONN: SIZE ____ POSITION ____

DISCHARGE CONN: SIZE ____ POSITION ____

CONN. RATING ____ TYPE ____

PACKING TYPE ____

LANTERN RINGS ____ MATERIAL ____

COOLING ____

BEARINGS: TYPE ____ GREASE ____ OIL ____

IMPELLER: TYPE ____ SIZE FUR. ____ MAX. ____

VENT CONN: ____ DRAIN CONN. ____

FLUSHING CONNECTION: ____

DRIVER

FURNISHED WITH PUMP ____ BY OTHERS ____

TYPE: ____

FRAME: ____

MANUFACTURER: ____

ENCLOSURE ____

VOLTS ____ PHASE ____ CYCLE ____

HP ____ RPM ____

BEARINGS ____ LUBRICATION ____

COUPLING GUARD ____

NOTES:

5.4.20 Freshwater Pump

In a lime FGD system, the most likely points at which freshwater would enter are the slakers, pump seals, and mist eliminators. The pump, if one is needed for this service, can be a standard centrifugal pump.

The important information that must be specified includes physico-chemical properties of the service water, available NPSH, materials of construction, type of drive, and motor.

Table 5.4-18 is an engineering data sheet for a typical freshwater pump vendor.

5.4.21 Thickener

To reduce the volume of wastes, most systems use a thickener to concentrate solids. Since the thickener has an important role in the water balance, the sludge characteristics, and in some cases the chemical reactions, care should be taken in its design. The following factors must be considered:

1. Corrosion
2. Solids concentration
3. Clarification
4. Recirculation
5. Solids removal

5.4.21.1 Corrosion--

Thickeners in lime scrubber systems are subject to wide variances in pH. Underflow slurry has been known to be as low as 4 when operating in very extreme upset conditions, and overflow pH can be as high as 11. Under normal operations, the pH of both the overflow and underflow will fluctuate around the operating pH of the scrubber. The pH gradient, from highly alkaline to medium-high acidity, brings a need for corrosion protection throughout the thickener. To prevent acid attack, the walls must be coated with epoxy or rubber. The floor of the thickener should be lined or made of concrete. The rake and the lifting mechanism should be rubber-coated stainless steel or rubber-coated alloy. Gear boxes should be sealed, and all walkways and support steel should be galvanized and properly coated. For additional detailed information, refer to the EPRI report entitled, "Sludge Dewatering Methods for Flue Gas Cleaning Products."

5.4.21.2 Solids Concentration--

Solids concentration in thickeners varies significantly from site to site. The calcium sulfite-to-sulfate ratio has an important impact on settling rates. The use of magnesium to enhance the efficiency of SO_2 removal causes lower settling

Table 5.4-18. EPRI LIME FGD SYSTEM DATA BOOK
FRESHWATER PUMP SPECIFICATIONS

COMPANY ____________ LOCATION ____________

EQUIPMENT NO. ________ FOR USE ON ________ TOTAL NO. REQUIRED ________

SUPPLIER ________ P.O. NO. ________ PRICE EACH $ ________

GENERAL INFORMATION

TYPE ____________

DUTY: CONTINUOUS ________ INTERMITTENT ________

SERVICE ____________

PROCESS INFORMATION

LIQUID: ____________

DESIGN FLOW: NORMAL ________ MAX ________ GPM

PUMPING TEMPERATURE ________ °F

SP. GR. @ PUMPING TEMPERATURE ________

VISCOSITY @ PUMPING TEMPERATURE ________

VAPOR PRESS. @ PUMP TEMP. ________ (FT.LIQ.)

PH VALUE ________

CORROSIVE MATERIAL ________

SOLIDS (MAX. DIA.) ________

HYDRAULIC INFORMATION ________ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+) ________

STATIC SUCTION LIFT (-): HEAD (+) ________

SUCTION FRICTION HEAD (-) ________

TOTAL SUCTION HEAD (17+18+19) ________

STATIC DISCHARGE HEAD ________

DISCHARGE FRICTION HEAD ________

DISCHARGE PRESS. ABOVE LIQ. (ABS.) ________

TOTAL DISCHARGE HEAD (21+22+23) ________

TOTAL DYNAMIC HEAD (24-20) ________

NPSH AVAILABLE (20-13) ________

NPSH REQUIRED ________

PUMP

MANUFACTURER ________

RPM ________

PERFORMANCE CURVE ________

SERIAL NO. ________

BPH @ SERVICE CONDITIONS ________

@ MAX. FLOW FOR IMPELLER ________

ROTATION @ DRIVE SHAFT END ________

COPIES REQUIRED OF: ________

PERFORMANCE CURVES ________

DIMENSION DRWGS. ________

OPERATING AND MAINTENANCE INSTRUCTIONS ________

MATERIALS

MATERIAL CODE - EXTERNAL CASING ________ INTERNAL PARTS ____

I - CAST IRON	INTERNALS CODE	I	B	S	C
B - BRONZE	IMPELLER	I	B	S	C
S - STEEL	INNER CASE PARTS	I	B	S	C
C - 11-13% CHROME	SLEEVE (PACKED)	Ch	Ch	Af	Af
A - ALLOY	SLEEVE (SEAL)	C	C	C	C
h - HARDENED	WEAR RINGS		B	Ch	Ch
f - FACED	SHAFT	S	S	S	S
	LANTERN RING				
	PACKING GLAND				

SUCTION CONN: SIZE ________ POSITION ________

DISCHARGE CONN: SIZE ________ POSITION ________

CONN. RATING ________ TYPE ________

PACKING TYPE ________

LANTERN RINGS ________ MATERIAL ________

COOLING ________

BEARINGS: TYPE ________ GREASE ________ OIL ____

IMPELLER: TYPE ________ SIZE FUR. ________ MAX. ________

VENT CONN: ________ DRAIN CONN. ________

FLUSHING CONNECTION: ________

DRIVER ________

FURNISHED WITH PUMP ________ BY OTHERS ________

TYPE: ________

FRAME: ________

MANUFACTURER: ________

ENCLOSURE ________

VOLTS ________ PHASE ________ CYCLE ____

HP ________ RPM ________

BEARINGS ________ LUBRICATION ________

COUPLING GUARD ________

NOTES:

rates. For proper design, settling tests should be performed on the sludge actually produced by the system. However, since this is normally impossible (except for duplicate systems), absorber effluent should be tested from a plant using a coal and scrubbing system as similar as possible.

5.4.21.3 Clarification--

The primary purpose of thickeners is to regulate the solids content of the underflow. Clarification is also important since the liquid is recycled to the system. Clarification of the liquid should be sufficient to prevent damage to the recycle pumps (if the liquid is used as pump seal water). The maximum solids content should be the design criterion, with the minimum solids level variable as a function of system load.

5.4.21.4 Recirculation--

Recirculation of underflow liquid has two functions. One is to prevent plugging of the underflow pipeline. The second is to guarantee a uniform flow to the thickener. The design of the thickener should consider an underflow recirculation option, to account for changes in solids loading when the scrubber is operating at turndown or with a lower sulfur coal.

5.4.21.5 Solids Removal--

Thickeners should be designed with rake mechanisms that can handle varying solids levels in the thickener. Because of the varying amounts of sludge that may be produced, the thickener must have a limitorque system to prevent the rake drive from breaking due to excessive torque. For more details, refer to the EPRI document entitled, "Sludge Dewatering Methods for Flue Gas Cleaning Products."

Table 5.4-19 is a typical specification for a thickener to be completed by the utility, architect/engineer, or system supplier for the thickener vendor.

5.4.22 Flocculant Proportioning Pump

Flocculant is usually added to the thickener by a reciprocating pump, which can be of a piston, plunger, or diaphragm type. The pump is invariably associated with a check valve in the discharge piping and is characterized by its pulsating flow.

Diaphragm pumps have no packings and seals exposed to the liquid pumped. It is possible to mount the pumping head of a low-capacity diaphragm pump in a location entirely separate from the drive. A major consideration in choosing a diaphragm pump, however, is the frequency of diaphragm failure. The flexible diaphragm, fabricated of metal, rubber, or plastic, has a shorter life than a piston or a plunger; and routine maintenance procedures should be established accordingly.

Table 5.4-19. EPRI LIME FGD SYSTEM DATA BOOK THICKENER SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO. ________

COMPUTED BY ________ DATE ________ PROJ. NO. ________

COMPANY ________ LOCATION ________

EQUIPMENT NO. ________ FOR USE ON ________ TOTAL NO. REQ'D. ________

SUPPLIER ________ P.O. NO. ________ PRICE EACH $ ________

1	GENERAL INFORMATION			
2				
3				
		PROCESS INFORMATION		
4	ABSORBER BLEED: FLOW	GPM, pH	TEMP.	°F
5	SOLIDS COMPOSITION, % (DRY BASIS):	$CaSO_3 \cdot 1/2\ H_2O$	$CaSO_4 \cdot 2\ H_2O$	Ash
6	SOLIDS REQ'D.: UNDERFLOW	MIN, OVERLFOW	MAX.	
		CENTRAL COLUMN		
7	MATERIAL	THK.		
8	SIZE			
		DRIVE UNIT		
9	TORQUE: OPERATING	FT LBS, CUT-OUT	FT LBS	
10	GEAR: TYPE	MATERIAL	SIZE	
11	REDUCER: TYPE	MATERIAL	SIZE	
12	BEARINGS: TYPE	MATERIAL	SIZE	
13	SUPPORT: TYPE	MATERIAL	SIZE	
		MOTOR		
14	HP	VOLTS	PHASE	HERTZ
15	OVERLOAD DEVICE: TYPE			
		TORQUE CAGE AND INFLUENT BAFFLE		
16	CARE MATERIAL:	BAFFLE: DIA	HT	THK.
		TRUSS ARMS		
17	NO.:	PIVOT AXIS INCLINATION	MATERIAL	
		SCRAPER BLADES		
18	MATL:	THK.	in., DEEP	in.
		EFFLUENT WEIR		
19	MATL:	THK.	in., DEEP	in.
20	NOTCH: TYPE	NO.		
		BRIDGE WALKWAY		
21	SIZE: WIDE	THK., MAX. LB/FT^2		
22	HANDRAILS: TYPE	SIZE		

SPECIAL INSTRUCTIONS:

Table 5.4-20 is the engineering data sheet for a typical reciprocating pump.

5.4.23 Thickener Underflow Pump

The thickener underflow pump performs several duties in lime slurry systems. The primary function is to remove solids from the bottom of the thickener, then transfer the sludge to one of three destinations: a waste pond, a thickener underflow transfer tank, or a vacuum filter. Depending on the destination, the pumping head may vary significantly for a uniform solids content slurry. The underflow pump must be designed to handle high solids concentration with abrasive components and, during upset conditions, corrosive conditions. Although the underflow from a thickener should have a pH between 7 and 8, early systems had insufficient pH control and suffered severe corrosion at the pump. Even though rubber-lined pumps should not be required, in many cases they are used as extra protection.

The pumps should have water seals to prevent erosion of the pump shafts. Each seal water supply should be individually controlled. The type of downstream equipment or the method of solids control affects the size of the thickener underflow pump. If solids are recirculated to maintain solids concentration in the thickener, then the pump must be oversized. If possible, the control system should be designed so that the thickener underflow pump operates at a continuous uniform rate. However, intermittent or variable operation also brings the need for an oversized pump.

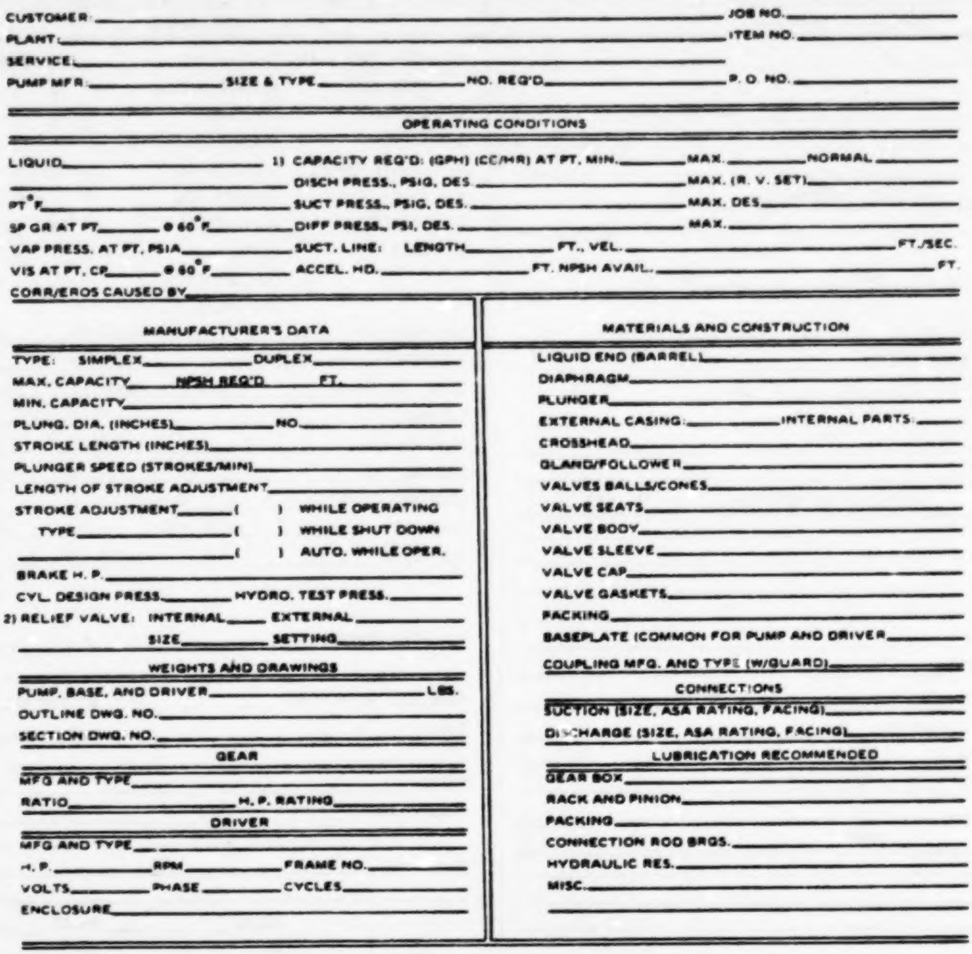
Table 5.4-21 is a typical specification to be completed by the utility, architect/engineer, or system supplier for the pump vendor.

5.4.24 Thickener Overflow Pump

The thickeners are normally so arranged that overflow goes by gravity to a collection tank. From this tank, one or more pumps return the clarified liquor to the system. Thickener overflow has a variety of uses: as dilution water for stabilized lime slurry, prequencher water, wash water for mist eliminators, recycle water to the recirculation tank of the absorber, and makeup water for an ash disposal system.

Because of this wide variety of uses, the designer should determine the end use before the pump specification is prepared. The pump head will vary considerably between uses. In addition, the following must be considered when specifying the thickener overflow pump:

Table 5.4-20. EPRI LIME FGD SYSTEM DATA BOOK FLOCCULANT PROPORTIONING PUMP SPECIFICATIONS



CUSTOMER ____ JOB NO. ____
PLANT ____ ITEM NO. ____
SERVICE ____
PUMP MFR ____ SIZE & TYPE ____ NO. REQ'D ____ P. O. NO. ____

OPERATING CONDITIONS

LIQUID ____ 1) CAPACITY REQ'D: (GPH) (CC/HR) AT PT, MIN. ____ MAX. ____ NORMAL ____
____ DISCH PRESS., PSIG, DES ____ MAX. (R. V. SET) ____
PT °F ____ SUCT PRESS., PSIG, DES. ____ MAX. DES ____
SP GR AT PT ____ @ 60°F ____ DIFF PRESS., PSI, DES. ____ MAX. ____
VAP PRESS. AT PT, PSIA ____ SUCT. LINE: LENGTH ____ FT., VEL. ____ FT./SEC.
VIS AT PT, CP ____ @ 60°F ____ ACCEL. HD. ____ FT. NPSH AVAIL. ____ FT.
CORR/EROS CAUSED BY ____

MANUFACTURER'S DATA

TYPE: SIMPLEX ____ DUPLEX ____
MAX. CAPACITY ____ NPSH REQ'D ____ FT. ____
MIN. CAPACITY ____
PLUNG. DIA. (INCHES) ____ NO. ____
STROKE LENGTH (INCHES) ____
PLUNGER SPEED (STROKES/MIN) ____
LENGTH OF STROKE ADJUSTMENT ____
STROKE ADJUSTMENT ____ ( ) WHILE OPERATING
TYPE ____ ( ) WHILE SHUT DOWN
____ ( ) AUTO. WHILE OPER.
BRAKE H. P. ____
CYL. DESIGN PRESS. ____ HYDRO. TEST PRESS. ____
2) RELIEF VALVE: INTERNAL ____ EXTERNAL ____
SIZE ____ SETTING ____

WEIGHTS AND DRAWINGS

PUMP, BASE, AND DRIVER ____ LBS.
OUTLINE DWG. NO. ____
SECTION DWG. NO. ____

GEAR

MFG AND TYPE ____
RATIO ____ H. P. RATING ____

DRIVER

MFG AND TYPE ____
H. P. ____ RPM ____ FRAME NO. ____
VOLTS ____ PHASE ____ CYCLES ____
ENCLOSURE ____

MATERIALS AND CONSTRUCTION

LIQUID END (BARREL) ____
DIAPHRAGM ____
PLUNGER ____
EXTERNAL CASING: ____ INTERNAL PARTS: ____
CROSSHEAD ____
GLAND/FOLLOWER ____
VALVES BALLS/CONES ____
VALVE SEATS ____
VALVE BODY ____
VALVE SLEEVE ____
VALVE CAP ____
VALVE GASKETS ____
PACKING ____
BASEPLATE (COMMON FOR PUMP AND DRIVER ____
COUPLING MFG. AND TYPE (W/GUARD) ____

CONNECTIONS

SUCTION (SIZE, ASA RATING, FACING) ____
DISCHARGE (SIZE, ASA RATING, FACING) ____

LUBRICATION RECOMMENDED

GEAR BOX ____
RACK AND PINION ____
PACKING ____
CONNECTION ROD BRGS. ____
HYDRAULIC RES. ____
MISC. ____

NOTES:

1) CATIONIC AND/OR ANIONIC POLYELECTROLYTE.

2) EXTERNAL RELIEF VALVE SHALL BE FURNISHED BY PURCHASER AND SHALL BE MOUNTED ON THE DISCHARGE PIPING. INTERNAL RELIEF VALVES SHALL BE FURNISHED BY VENDOR AS INTEGRAL COMPONENT IN HYDRAULIC DRIVE SYSTEM.

* VENDOR TO SPECIFY.

Table 5.4-21. EPRI LIME FGD SYSTEM DATA BOOK
THICKENER UNDERFLOW PUMP SPECIFICATIONS

COMPANY ________ LOCATION ________

EQUIPMENT NO. ________ FOR USE ON ________ TOTAL NO. REQUIRED ________

SUPPLIER ________ P.O. NO. ________ PRICE EACH $ ________

GENERAL INFORMATION

TYPE ________

DUTY: CONTINUOUS ________ INTERMITTENT ________

SERVICE ________

PROCESS INFORMATION

LIQUID: ________

DESIGN FLOW: NORMAL ________ MAX ________ GPM

PUMPING TEMPERATURE ________ °F

SP. GR. @ PUMPING TEMPERATURE ________

VISCOSITY @ PUMPING TEMPERATURE ________

VAPOR PRESS. @ PUMP TEMP. ________ (FT.LIQ.)

PH VALUE ________

CORROSIVE MATERIAL ________

SOLIDS (MAX. DIA.) ________

HYDRAULIC INFORMATION ________ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+) ________

STATIC SUCTION LIFT (-): HEAD (+) ________

SUCTION FRICTION HEAD (-) ________

TOTAL SUCTION HEAD (17+18+19) ________

STATIC DISCHARGE HEAD ________

DISCHARGE FRICTION HEAD ________

DISCHARGE PRESS. ABOVE LIQ. (ABS.) ________

TOTAL DISCHARGE HEAD (21+22+23) ________

TOTAL DYNAMIC HEAD (24-20) ________

NPSH AVAILABLE (20-13) ________

NPSH REQUIRED ________

PUMP

MANUFACTURER ________

RPM ________

PERFORMANCE CURVE ________

SERIAL NO. ________

BPH @ SERVICE CONDITIONS

@ MAX. FLOW FOR IMPELLER ________

ROTATION @ DRIVE SHAFT END ________

COPIES REQUIRED OF: ________

PERFORMANCE CURVES ________

DIMENSION DRWGS. ________

OPERATING AND MAINTENANCE INSTRUCTIONS ________

MATERIALS

MATERIAL CODE - EXTERNAL CASING ________ INTERNAL PARTS ________

I - CAST IRON	INTERNALS CODE	I	B	S	C
B - BRONZE	IMPELLER	I	B	S	C
S - STEEL	INNER CASE PARTS	I	B	S	C
C - 11-13% CHROME	SLEEVE (PACKED)	Ch	Ch	Af	Af
A - ALLOY	SLEEVE (SEAL)	C	C	C	C
h - HARDENED	WEAR RINGS		B	Ch	Ch
f - FACED	SHAFT	S	S	S	S
	LANTERN RING				
	PACKING GLAND				

SUCTION CONN: SIZE ________ POSITION ________

DISCHARGE CONN: SIZE ________ POSITION ________

CONN. RATING ________ TYPE ________

PACKING TYPE ________

LANTERN RINGS ________ MATERIAL ________

COOLING ________

BEARINGS: TYPE ________ GREASE ________ OIL ________

IMPELLER: TYPE ________ SIZE FUR. ________ MAX. ________

VENT CONN: ________ DRAIN CONN. ________

FLUSHING CONNECTION: ________

DRIVER ________

FURNISHED WITH PUMP ________ BY OTHERS ________

TYPE: ________

FRAME: ________

MANUFACTURER: ________

ENCLOSURE ________

VOLTS ________ PHASE ________ CYCLE ________

HP ________ RPM ________

BEARINGS ________ LUBRICATION ________

COUPLING GUARD ________

NOTES:

1. Corrosion
2. Pump seals

5.4.24.1 Corrosion--

The dissolved salts content of the overflow liquor is high. Therefore, to avoid corrosion, the pump must be made of high-alloy steel or be rubber lined.

5.4.24.2 Pump Seals--

Since the pump may on occasion have to handle high solids levels, water seals should be used instead of mechanical seals. Individually controlled seal water systems should be used to protect the shaft from solids erosion.

Table 5.4-22 is a typical specification to be completed by the utility, architect/engineer, or equipment supplier for the pump vendor.

5.4.25 Thickener Overflow Tank

The thickener overflow tank acts as a surge tank and stores supernatant liquid from the thickener to be pumped to the various locations in the scrubbing system to maintain a water balance. Factors to be considered in the design of the thickener overflow tank include:

1. Corrosion
2. Erosion
3. Tank size

5.4.25.1 Corrosion--

The pH of the thickener overflow should be between 6 and 7; however, pH excursions may occur. The tank, therefore, should be made of carbon steel clad with stainless steel, or carbon steel lined with rubber or fiberglass.

5.4.25.2 Erosion--

Unless there are upsets in the thickener, there should be no large quantities of slurry solids in the overflow tank, and serious erosion problems should not occur. Tanks may be lined with stainless steel, rubber, or fiberglass.

5.4.25.3 Tank Size--

In many cases, the thickener overflow is reused to achieve a water balance in the scrubbing system. The tank should be sized to allow for some system swings. Adequate NPSH for the overflow pump must also be considered.

Table 5.4-23 illustrates a typical specification as it would be completed by the utility, architect/engineer, or system supplier for the tank vendor.

Table 5.4-22. EPRI LIME FGD SYSTEM DATA BOOK
THICKENER OVERFLOW PUMP SPECIFICATIONS

COMPANY ____________ LOCATION ____________
EQUIPMENT NO. ____________ FOR USE ON ____________ TOTAL NO. REQUIRED ____________
SUPPLIER ____________ P.O. NO. ____________ PRICE EACH $ ____________

GENERAL INFORMATION

TYPE ____________
DUTY: CONTINUOUS ____________ INTERMITTENT ____________
SERVICE ____________

PROCESS INFORMATION

LIQUID: ____________
DESIGN FLOW: NORMAL ________ MAX ________ GPM
PUMPING TEMPERATURE ____________ °F
SP. GR. @ PUMPING TEMPERATURE ____________
VISCOSITY @ PUMPING TEMPERATURE ____________
VAPOR PRESS. @ PUMP TEMP. ________ (FT.LIQ.)
PH VALUE ____________
CORROSIVE MATERIAL ____________
SOLIDS (MAX. DIA.) ____________

HYDRAULIC INFORMATION ________ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+) ____________
STATIC SUCTION LIFT (-): HEAD (+) ____________
SUCTION FRICTION HEAD (-) ____________
TOTAL SUCTION HEAD (17+18+19) ____________
STATIC DISCHARGE HEAD ____________
DISCHARGE FRICTION HEAD ____________
DISCHARGE PRESS. ABOVE LIQ. (ABS.) ____________
TOTAL DISCHARGE HEAD (21+22+23) ____________
TOTAL DYNAMIC HEAD (24-20) ____________
NPSH AVAILABLE (20-13) ____________
NPSH REQUIRED ____________

PUMP

MANUFACTURER ____________
RPM ____________
PERFORMANCE CURVE ____________
SERIAL NO. ____________
BPH @ SERVICE CONDITIONS
@ MAX. FLOW FOR IMPELLER ____________
ROTATION @ DRIVE SHAFT END ____________
COPIES REQUIRED OF: ____________
PERFORMANCE CURVES ____________
DIMENSION DRWGS. ____________
OPERATING AND MAINTENANCE INSTRUCTIONS ____________

MATERIALS

MATERIAL CODE - EXTERNAL CASING ____________ INTERNAL PARTS ______

I - CAST IRON	INTERNALS CODE	I	B	S	C
B - BRONZE	IMPELLER	I	B	S	C
S - STEEL	INNER CASE PARTS	I	B	S	C
C - 11-13% CHROME	SLEEVE (PACKED)	Ch	Ch	Af	Af
A - ALLOY	SLEEVE (SEAL)	C	C	C	C
h - HARDENED	WEAR RINGS		B	Ch	Ch
f - FACED	SHAFT	S	S	S	S
	LANTERN RING				
	PACKING GLAND				

SUCTION CONN: SIZE ____________ POSITION ____________
DISCHARGE CONN: SIZE ____________ POSITION ____________
CONN. RATING ____________ TYPE ____________
PACKING TYPE ____________
LANTERN RINGS ____________ MATERIAL ____________
COOLING ____________
BEARINGS: TYPE ________ GREASE ________ OIL ____
IMPELLER: TYPE ________ SIZE FUR. ________ MAX. ____
VENT CONN: ____________ DRAIN CONN. ____________

FLUSHING CONNECTION: ____________
DRIVER ____________
FURNISHED WITH PUMP ____________ BY OTHERS ____________
TYPE: ____________
FRAME: ____________
MANUFACTURER: ____________
ENCLOSURE ____________
VOLTS ________ PHASE ________ CYCLE ____
HP ________ RPM ________
BEARINGS ____________ LUBRICATION ____________
COUPLING GUARD ____________

NOTES:

Table 5.4-23. EPRI LIME FGD SYSTEM DATA BOOK THICKENER OVERFLOW TANK SPECIFICATIONS

Sheet of

REV

CUSTOMER

PLANT LOCATION

SERVICE

JOB NO.

EQUIPT. NO.

FILE NO.

P.O. NO.

Type of Tank

Size: Diam. Height Capacity

GENERAL NOTES

1) For required capacity as shown, Mfg. to advise diameter and height of tank for the most economical utilization of plate.
2) Nozzle orientation to be furnished later.
3) Nozzle location and design tube furnished later with mechanical design.
4) Ladder Clips & Ladder:
   ________ Inside ________ Outside
5) Design P.________ Design T________
6) Paint ________
7) Lining - Fiberglass or rubber Note 1

NOZZLES	MARK	NO.	SIZE	RATING
Inlet				
Outlet				
Drawoff Elbow				
P & V Vent				
Level Gage				
Thermowell				
Roof Manhole				
Shell Manhole				

DESIGN DATA

Tank Material Min. Plate Thick SP GR

Corrosion Allowance: Shell in.; Bottom in.; Roof in.

APPURTENANCES (BY)

Level Gage or Gate Column: Yes No Type

Make Fig. or Equal Float

Pressure & Vacuum Vent Valve: Yes No Pressure oz.

Make Fig. or Equal Vacuum oz.

Gage Hatch: Yes No. Make Fig. or Equal

Thermometer Well: Yes No Length In

Make Model or Equal Material

Thermometer: Yes No Stem Length In

Make Model or Equal Range

REMARKS:

5.4.26 Centrifuges

To date, centrifuges have only been used experimentally for dewatering scrubber sludges. They do offer a consistent product that is uniform and easily handled. If a consistent sludge product is required as part of a regulation program, then centrifuges may be used extensively. The lack of clarified centrate is not a problem in lime slurry systems, since the centrate can be recycled to the scrubbing system. The following factors should be considered in specifying a centrifuge for lime slurry applications:

1. Materials of construction
2. Rotational speed
3. Conveyor

5.4.26.1 Materials of Construction--

The erosive and sometimes corrosive nature of scrubber sludges requires that all liquid contact materials in the centrifuge be made of 316L stainless steel. The tips of the conveyor should be made of tungsten carbide to reduce abrasive wear.

5.4.26.2 Rotational Speed--

Rotational speed should be midrange, 3000 rpm or less, to gain some of the benefits of high-speed clarification while preventing excessive abrasions and difficult solids discharge. If centrifuge speeds are too high, the conveyor and the bowl will lock.

5.4.26.3 Conveyor Speed--

The screw conveyor within the bowl should turn at the minimum speed required to remove solids without making excessive turbulence. Since the scrubber cake rates may vary, a variable-speed conveyor should be specified.

Table 5.4-24 is an illustration of a specification as it might be prepared by a utility, architect/engineer, or systems supplier for the centrifuge vendor. For more details, refer to EPRI report, "Sludge Dewatering Methods for Flue Gas Cleaning Products."

5.4.27 Vacuum Filters

Vacuum filters are used at several locations to dewater lime slurry sludges. Although they are bulky and use a significant amount of energy, they respond well to varying sludge properties and quantities. The following factors should be considered in specifying a vacuum filter:

Table 5.4-24. EPRI LIME FGD SYSTEM DATA BOOK CENTRIFUGAL SEPARATOR SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO. ________
COMPUTED BY ________ DATE ________ PROJ. NO. ________
COMPANY ________ LOCATION ________
EQUIPMENT NO. ________ FOR USE ON ________ TIME NO. REQ'D. ________
SUPPLIER ________ P.O. NO. ________ PRICE EACH $________

	DUTY	
1	SLUDGE, MAX.	LB/HR
2	LIQUID TEMPERATURE:	°F
3	SOLIDS:	LB/HR
4	PRESSURE, IN:	
5	PRESSURE, OUT:	
6	Δ P ACROSS SEPARATOR:	
7	INSTALLATION: INDOOR ☐ OUTDOOR ☐	
8	OPERATION: CONTINUOUS ☐ INTERMITTENT ☐	
9	CONSTANT: PRESSURE ☐ FLOW ☐	
10	WIND VELOCITY:	M.P.H.
11	SEISMIC LOAD:	G'S.
12	SPEED RPM	
13	MOTOR: TYPE , VOLTS HERTZ	
14	DRIVE: TYPE , MATERIAL	
15	SOLIDS STORAGE	CU.FT.
	SOLIDS DESCRIPTION	
16	COMPOSITION	
17	LB/CU.FT. S.G.	
18	TEMPERATURE:	°F.
19		
20		
21		
22	CORROSIVE ☐ HYGROSCOPIC ☐ ABRASIVE ☐	
23	PERMEABILITY:	
24	COMPRESSIBILITY:	
25	CAKE THICKNESS:	MAX.

	PHYSICAL DESCRIPTION		
26	VESSEL MAT'L.		
27	THICKNESS:		
28	LEG SUPPORTED ☐ BRACKET SUPPORTED ☐		
29	VESSEL SIZE:		
30	PIPE LINE	SLUDGE	LIQUID OUT
31	SIZE		
32	WALL THICKNESS		
33	MATERIAL		
	INTERNALS		
34	SCREEN: SIZE , MATERIAL		
35	OPENINGS: SIZE , PITCH		
36	CLOTH: MATERIAL , THK.		
37	BREAKING TENACITY:		
38	SPECIFIC RESISTANCE:		
39			
40			
	SPECIAL INSTRUCTIONS		

1. Materials of construction
2. Drying time
3. Barometric legs
4. Filter medium

5.4.27.1 Materials of Construction--

To prevent corrosion, the piping and support members in a vacuum filter in lime slurry applications should be made of stainless steel. Drum heads in the filter can be made from carbon steel if sufficient corrosion allowances are provided.

5.4.27.2 Drying Time--

The drying zone in a vacuum filter should be designed for a 10-second drying time. If longer drying times are used, the sludge will crack. The drying air then short-circuits through the cracks and does not continue to dry the cake. This condition would require the purchase of an excessively large vacuum pump to pull in the excess air. The 10-second drying time maximizes the cake solids content of the filter cake without requiring an excessively large vacuum pump.

5.4.27.3 Barometric Legs--

To keep filtrate from going through the vacuum pump, a barometric leg should be installed to protect the pump by trapping liquid before the suction of the vacuum pump.

5.4.27.4 Filter Medium--

The filter medium should be cheap, durable, and noncorrosive, and it should allow easy cake discharge. In lime slurry applications, polypropylene appears to be the best material.

Table 5.4-25 is a typical specification for a vacuum filter to be prepared by a utility, architect/engineer, or system supplier for a vacuum filter vendor.

For more information, refer to EPRI report, "Sludge Dewatering Methods for Flue Gas Cleaning Products."

5.4.28 Filtrate or Centrate Pump

This pump returns the clarified filtrate from the centrifuge or vacuum filter to the scrubbing system. The liquid is normally returned to the thickener overflow tank or to the thickener itself. In either case, the solids content of the filtrate or centrate should be low and the pH should be 7 or greater. This pump should see the mildest duty of any process pump within the scrubbing system. The following factors should be considered when specifying the filtrate or centrate pump:

Table 5.4-25. EPRI LIME FGD SYSTEM DATA BOOK VACUUM FILTER SPECIFICATIONS

CHECKED BY ____ DATE ____ SPEC. NO. ____
COMPUTED BY ____ DATE ____ PROJ. NO. ____
COMPANY ____ LOCATION ____
EQUIPMENT NO. ____ FOR USE ON ____ TIME NO. REQ'D. ____
SUPPLIER ____ P.O. NO. ____ PRICE EACH $ ____

	DUTY		PHYSICAL DESCRIPTION		
1	SLUDGE, MAX. LB/HR	26	VESSEL MAT'L.		
2	LIQUID TEMPERATURE: °F	27	THICKNESS:		
3	SOLIDS: LB/HR	28	LEG SUPPORTED ☐ BRACKET SUPPORTED ☐		
4	PRESSURE, IN:	29	VESSEL SIZE:		
5	PRESSURE, OUT:	30	PIPE LINE	SLUDGE	LIQUID OUT
6	ΔP ACROSS SEPARATOR:	31	SIZE		
7	INSTALLATION: INDOOR ☐ OUTDOOR ☐	32	WALL THICKNESS		
8	OPERATION: CONTINUOUS ☐ INTERMITTENT ☐	33	MATERIAL		
9	CONSTANT: PRESSURE ☐ FLOW ☐		INTERNALS		
10	WIND VELOCITY: M.P.H.	34	SCREEN: SIZE , MATERIAL		
11	SEISMIC LOAD: G'S.	35	OPENINGS: SIZE , PITCH		
12	SPEED RPM	36	CLOTH: MATERIAL , THK.		
13	MOTOR: TYPE , VOLTS HERTZ	37	BREAKING TENACITY:		
14	DRIVE: TYPE , MATERIAL	38	SPECIFIC RESISTANCE:		
15	SOLIDS STORAGE CU.FT.	39			
	SOLIDS DESCRIPTION	40			
16	COMPOSITION		SPECIAL INSTRUCTIONS		
17	LB/CU.FT. S.G.				
18	TEMPERATURE: °F.				
19					
20					
21					
22	CORROSIVE ☐ HYGROSCOPIC ☐ ABRASIVE ☐				
23	PERMEABILITY:				
24	COMPRESSIBILITY:				
25	CAKE THICKNESS: MAX.				

1. Erosion
2. Corrosion
3. Pump seals

5.4.28.1 Erosion--

Operating upsets in the centrifuge or the vacuum filter may allow solids to enter the filtrate or centrate. Although these occurrences should be rare, the designer may want to protect against them. In this case, an erosion resistant alloy or rubber-lined pump should be used.

5.4.28.2 Corrosion--

In most thickeners on lime slurry systems, the pH of the underflow will be between 7 and 9 because of the unreacted lime in the slurry. Therefore, the feed to the vacuum filter or centrifuge is in the same range. In cases where the pH is so low that an erosion resistant alloy is not suitable, the thickener will not operate properly. Also, the vacuum filter could be stopped to protect a pump made of an erosion resistant alloy. From a corrosion and erosion standpoint, both erosion resistant alloy and rubber-lined pumps are suitable.

5.4.28.3 Pump Seals--

Since the pump on occasion handles solids, water seals should be used instead of mechanical seals. Individually controlled seal water systems should be used to protect the shaft from solids erosion.

Table 5.4-26 is a typical specification as it would be completed by the utility, architect/engineer, or equipment supplier for the pump vendor.

5.4.29 Fixation Additive Silos

The following factors are important in specifying a fixation additive storage silo:

1. Materials of construction
2. Conveying systems

5.4.29.1 Materials of Construction--

Cylindrical unlined carbon steel tanks with cone bottoms or concrete silos can be used for storing fixation additive.

5.4.29.2 Conveying Systems--

Either pneumatic or mechanical conveying systems are used to move additives. Pneumatic systems are more common and easier to maintain, but allow water vapor into the system if not operated in a closed flue manner. Larger fabric filters are required for silos handling pneumatically conveyed lime than for silos handling mechanically conveyed lime.

Table 5.4-26. EPRI LIME FGD SYSTEM DATA BOOK FILTRATE OR CENTRATE PUMP SPECIFICATIONS

COMPANY ____ LOCATION ____
EQUIPMENT NO. ____ FOR USE ON ____ TOTAL NO. REQUIRED ____
SUPPLIER ____ P.O. NO. ____ PRICE EACH $ ____

GENERAL INFORMATION

TYPE ____
DUTY: CONTINUOUS ____ INTERMITTENT ____
SERVICE ____

PROCESS INFORMATION

LIQUID: ____
DESIGN FLOW: NORMAL ____ MAX ____ GPM
PUMPING TEMPERATURE ____ °F
SP. GR. @ PUMPING TEMPERATURE ____
VISCOSITY @ PUMPING TEMPERATURE ____
VAPOR PRESS. @ PUMP TEMP. ____ (FT.LIQ.)
PH VALUE ____
CORROSIVE MATERIAL ____
SOLIDS (MAX. DIA.) ____

HYDRAULIC INFORMATION ____ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+) ____
STATIC SUCTION LIFT (-): HEAD (+) ____
SUCTION FRICTION HEAD (-) ____
TOTAL SUCTION HEAD (17+18+19) ____
STATIC DISCHARGE HEAD ____
DISCHARGE FRICTION HEAD ____
DISCHARGE PRESS. ABOVE LIQ. (ABS.) ____
TOTAL DISCHARGE HEAD (21+22+23) ____
TOTAL DYNAMIC HEAD (24-20) ____
NPSH AVAILABLE (20-13) ____
NPSH REQUIRED ____

PUMP

MANUFACTURER ____
RPM ____
PERFORMANCE CURVE ____
SERIAL NO. ____
BPH @ SERVICE CONDITIONS
@ MAX. FLOW FOR IMPELLER ____
ROTATION @ DRIVE SHAFT END ____
COPIES REQUIRED OF: ____
PERFORMANCE CURVES ____
DIMENSION DRWGS. ____
OPERATING AND MAINTENANCE INSTRUCTIONS ____

MATERIALS

MATERIAL CODE - EXTERNAL CASING ____ INTERNAL PARTS ____

I - CAST IRON	INTERNALS CODE	I	B	S	C
B - BRONZE	IMPELLER	I	B	S	C
S - STEEL	INNER CASE PARTS	I	B	S	C
C - 11-13% CHROME	SLEEVE (PACKED)	Ch	Ch	Af	Af
A - ALLOY	SLEEVE (SEAL)	C	C	C	C
h - HARDENED	WEAR RINGS		B	Ch	Ch
f - FACED	SHAFT	S	S	S	S
	LANTERN RING				
	PACKING GLAND				

SUCTION CONN: SIZE ____ POSITION ____
DISCHARGE CONN: SIZE ____ POSITION ____
CONN. RATING ____ TYPE ____
PACKING TYPE ____
LANTERN RINGS ____ MATERIAL ____
COOLING ____
BEARINGS: TYPE ____ GREASE ____ OIL ____
IMPELLER: TYPE ____ SIZE FUR. ____ MAX. ____
VENT CONN: ____ DRAIN CONN. ____

FLUSHING CONNECTION: ____

DRIVER ____

FURNISHED WITH PUMP ____ BY OTHERS ____
TYPE: ____
FRAME: ____
MANUFACTURER: ____
ENCLOSURE ____
VOLTS ____ PHASE ____ CYCLE ____
HP ____ RPM ____
BEARINGS ____ LUBRICATION ____
COUPLING GUARD ____

NOTES:

5.4.30 Fixation Tank or Pug Mill

The fixation tank is used to mix a fixation agent with the spent slurry (sludge). In the Dravo system, the clarifier underflow is used as a feed, the fixation agent is added, and the mixed product flows or is pumped to a sludge pond. In the IUCS system, lime, fly ash, and sludge from a vacuum filter are mixed in a pug mill. The product from the pug mill is a moist cake. The following factors should be considered in designing a fixation tank or a pug mill:

1. Corrosion
2. Erosion
3. Tank size

5.4.30.1 Corrosion--

The spent slurry has a pH of 8 or more; therefore, corrosion is not a major problem. The equipment could be stopped to protect it from low pH swings.

5.4.30.2 Erosion--

Erosion is the major design consideration. To achieve proper mixing of the slurry, high torque agitators are needed. The rapid movement of the slurry and fixation agents against the tank walls heightens abrasive action. For reduced maintenance, the tank walls and bottom should be rubber lined.

5.4.30.3 Tank Size--

The tank must be designed to give proper mixing. If slurry is pumped from the tank, then NPSH requirements of the pump must be considered.

Table 5.4-27 is a typical specification as it would be completed by the utility, architect/engineer, or equipment supplier for the fixation tank.

5.4.31 Sludge Disposal Pump

In an actual installation (Bruce Mansfield), sludge pumps are only used to pump fixated thickener underflow to a disposal pond. In this case, the sludge can be pumped as far as several miles to remote sludge disposal areas. If so, a high-head (700 psi) pump is required. To meet this discharge pressure, reciprocating pumps are necessary. If the sludge disposal were on the site, centrifugal rubber-lined pumps or erosion resistant alloy pumps similar to thickener underflow pumps could be used. (Sludge pumps cannot be used after vacuum filtration or centrifuging.)

Factors to be considered when specifying a sludge disposal pump include:

Table 5.4-27. EPRI LIME FGD SYSTEM DATA BOOK FIXATION TANK SPECIFICATIONS

Sheet of

R E V

CUSTOMER

PLANT LOCATION

SERVICE

JOB NO.

EQUIPT. NO.

FILE NO.

P.O. NO.

Type of Tank

Size: Diam. Height Capacity

GENERAL NOTES

1) For required capacity as shown, Mfg. to advise diameter and height of tank for the most economical utilization of plate.
2) Nozzle orientation to be furnished later.
3) Nozzle location and design tube furnished later with mechanical design.
4) Ladder Clips & Ladder:
   ______ Inside ______ Outside
5) Design P.______ Design T______
6) Paint
7) Lining - Fiberglass or rubber Note 1

NOZZLES	MARK	NO.	SIZE	RATING
Inlet				
Outlet				
Drawoff Elbow				
P & V Vent				
Level Gage				
Thermowell				
Roof Manhole				
Shell Manhole				

DESIGN DATA

Tank Material Min. Plate Thick SP GR

Corrosion Allowance: Shell in.; Bottom in.; Roof in.

APPURTENANCES (BY)

Level Gage or Gate Column: Yes No Type

Make Fig. or Equal Float

Pressure & Vacuum Vent Valve: Yes No Pressure oz.

Make Fig. or Equal Vacuum oz.

Gage Hatch: Yes No. Make Fig. or Equal

Thermometer Well: Yes No Length In

Make Model or Equal Material

Thermometer: Yes No Stem Length In

Make Model or Equal Range

REMARKS:

1. Corrosion
2. Erosion
3. Pump seals
4. Pumping distance and head

5.4.31.1 Corrosion--

Excess lime should cause the sludge to have a pH between 7 and 9. Low pH should only occur during system upsets; therefore, erosion resistant alloy or rubber-lined pumps would be acceptable from a corrosion standpoint. During the rare pH excursions, the sludge disposal system could and should be stopped to protect the erosion resistant alloy pump.

5.4.31.2 Erosion--

Sludge having a high solids content and containing abrasive fly ash requires rubber-lined or erosion resistant alloy pumps to prevent excessive pump wear.

5.4.31.3 Pump Seals--

Since the pump handles abrasive solids, seal water should be used instead of mechanical seals. Individually controlled seal water systems with alarms should be used to protect the shaft from erosion by the solids.

5.4.31.4 Pumping Distance and Head--

The ultimate disposal site affects the type of pump selected. Rubber-lined pumps are limited to 120 ft of head, erosion resistant alloy is limited by excess erosion to 400 ft of head, and reciprocating pumps are limited only by economic design.

Table 5.4-28 is a typical specification as it would be completed by the utility, architect/engineer, or equipment supplier for the pump vendor.

5.4.32 Sludge Conveying System

5.4.32.1 Belt Conveyor--

If the sludge is solid and nonthixotropic after the addition of the fixation agent and vacuum filtration, it can be transported to the disposal pond by the sludge conveying system. The most commonly used system is a belt conveyor that, given good routine maintenance, can outlast any other type of conveyor.

Belt conveyor design begins with the material to be handled. Since weight per cubic foot is an important factor, it should be determined accurately in an "as-handled" condition, rather than taken from published information. Lump size is another important factor. If the feed chute and the belt slope are properly designed, there is little problem with lumps falling off. Belt conveyor slopes are limited to a maximum of 30 degrees; those in the range of 18 to 20 degrees are more common.

Table 5.4-28. EPRI LIME FGD SYSTEM DATA BOOK
SLUDGE DISPOSAL PUMP SPECIFICATIONS

COMPANY ____ LOCATION ____
EQUIPMENT NO. ____ FOR USE ON ____ TOTAL NO. REQUIRED ____
SUPPLIER ____ P.O. NO. ____ PRICE EACH $ ____

GENERAL INFORMATION

TYPE ____
DUTY: CONTINUOUS ____ INTERMITTENT ____
SERVICE ____

PROCESS INFORMATION

LIQUID: ____
DESIGN FLOW: NORMAL ____ MAX ____ GPM
PUMPING TEMPERATURE ____ °F
SP. GR. @ PUMPING TEMPERATURE ____
VISCOSITY @ PUMPING TEMPERATURE ____
VAPOR PRESS. @ PUMP TEMP. ____ (FT.LIQ.)
PH VALUE ____
CORROSIVE MATERIAL ____
SOLIDS (MAX. DIA.) ____

HYDRAULIC INFORMATION ____ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+) ____
STATIC SUCTION LIFT (-): HEAD (+) ____
SUCTION FRICTION HEAD (-) ____
TOTAL SUCTION HEAD (17+18+19) ____
STATIC DISCHARGE HEAD ____
DISCHARGE FRICTION HEAD ____
DISCHARGE PRESS. ABOVE LIQ. (ABS.) ____
TOTAL DISCHARGE HEAD (21+22+23) ____
TOTAL DYNAMIC HEAD (24-20) ____
NPSH AVAILABLE (20-13) ____
NPSH REQUIRED ____

PUMP

MANUFACTURER ____
RPM ____
PERFORMANCE CURVE ____
SERIAL NO. ____
BPH @ SERVICE CONDITIONS
@ MAX. FLOW FOR IMPELLER ____
ROTATION @ DRIVE SHAFT END ____
COPIES REQUIRED OF: ____
PERFORMANCE CURVES ____
DIMENSION DRWGS. ____
OPERATING AND MAINTENANCE INSTRUCTIONS ____

MATERIALS

MATERIAL CODE - EXTERNAL CASING ____ INTERNAL PARTS ____

I - CAST IRON	INTERNALS CODE	I	B	S	C
B - BRONZE	IMPELLER	I	B	S	C
S - STEEL	INNER CASE PARTS	I	B	S	C
C - 11-13% CHROME	SLEEVE (PACKED)	Ch	Ch	Af	Af
A - ALLOY	SLEEVE (SEAL)	C	C	C	C
h - HARDENED	WEAR RINGS		B	Ch	Ch
f - FACED	SHAFT	S	S	S	S
	LANTERN RING				
	PACKING GLAND				

SUCTION CONN: SIZE ____ POSITION ____
DISCHARGE CONN: SIZE ____ POSITION ____
CONN. RATING ____ TYPE ____
PACKING TYPE ____
LANTERN RINGS ____ MATERIAL ____
COOLING ____
BEARINGS: TYPE ____ GREASE ____ OIL ____
IMPELLER: TYPE ____ SIZE FUR. ____ MAX. ____
VENT CONN: ____ DRAIN CONN. ____

FLUSHING CONNECTION: ____

DRIVER ____

FURNISHED WITH PUMP ____ BY OTHERS ____
TYPE: ____
FRAME: ____
MANUFACTURER: ____
ENCLOSURE ____
VOLTS ____ PHASE ____ CYCLE ____
HP ____ RPM ____
BEARINGS ____ LUBRICATION ____
COUPLING GUARD ____

NOTES:

* VENDOR TO STATE WITH QUOTE

The temperature and the chemical activity of the sludge play an important role in belt selection. Belts can be quickly damaged by high temperatures; a high-priced belt may prove most economical in the long run. The elastomers available for belt construction include Neoprene, Teflon, Buna-N rubber, and vinyl rubbers.

The belt conveyor tonnage requirement should be specified at the peak rather than the average load. It is advisable to work with a manufacturer to calculate the horsepower needed to drive a belt conveyor. Belt tension can be calculated from drive shaft horsepower. Since various combinations of width and ply thickness will develop the required strength, final selection is influenced by lump size, ability of the belt to form a trough, and ability of the belt to support the load between the idlers. Once final belt selection is made, idlers and return rolls can also be selected.

Table 5.4-29 is a typical engineering data sheet for a belt conveyor.

Care should be taken not to use conveyor belts and chutes for the transfer of unfixed thixotropic sludge. The vibrations in such a system would cause undesired liquefaction. If the sludge to be conveyed is gypsum, there is little chance that it will be thixotropic.

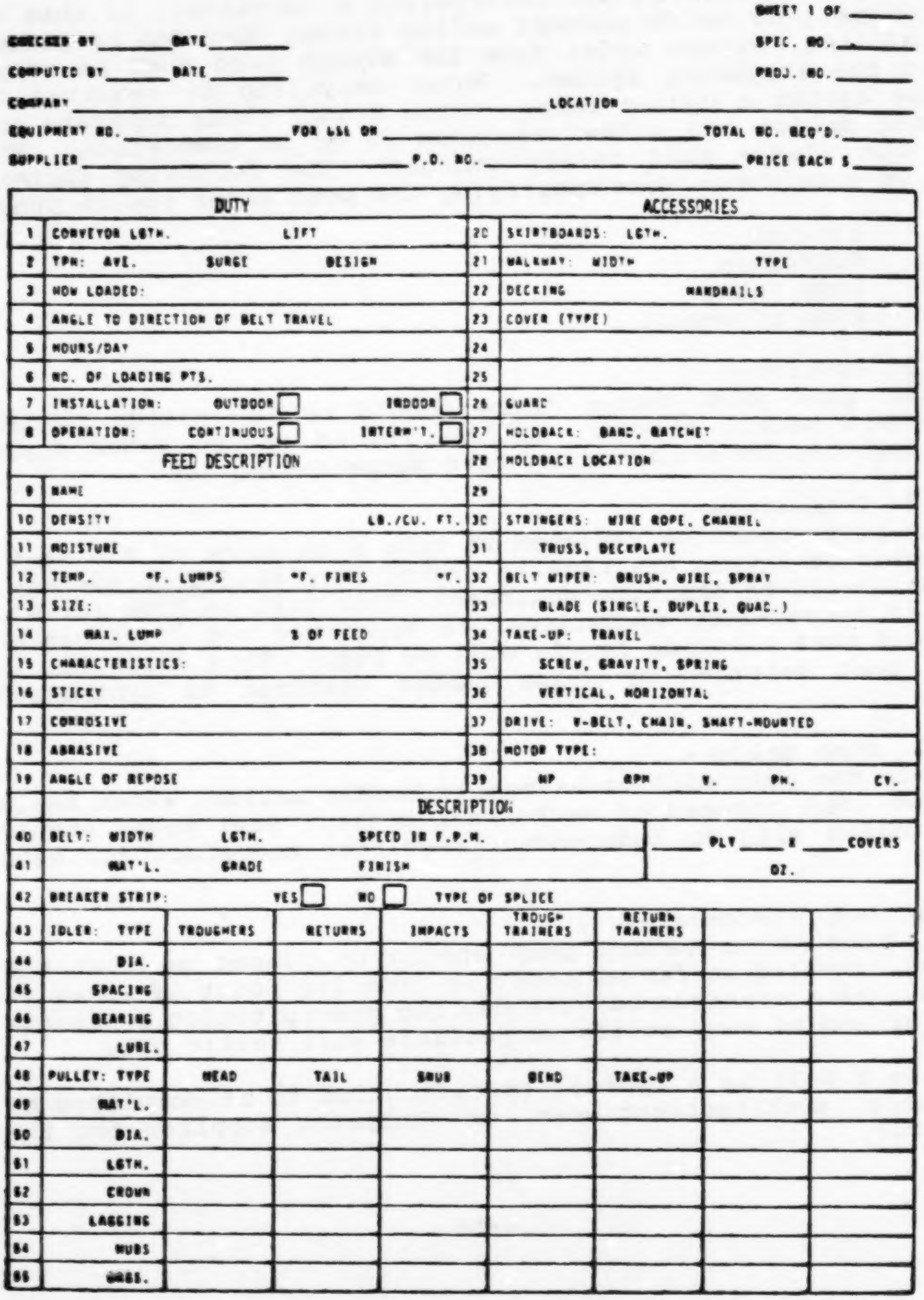
5.4.32.2 Screw Conveyor--

Another common sludge conveying system is the screw conveyor, which consists of a helical flight mounted on a shaft and turning in a trough. Power to convey must be transmitted through the shaft and is limited by its allowable size. Screw conveyor capacities are generally restricted to about 10,000 ft^3/h.

In addition to a wide variety of designs for the components, screw conveyors may be fabricated of several materials, ranging from cast iron to stainless steel. Since sections are coupled together, special attention should be given to bending stresses in the couplings. Screw conveyors operate at low rotating speeds, and the outer edge of the flight may be moving at a relatively high linear speed. This can create a wear problem, which can be reduced by the use of hard-surfaced edges, rubber covering, or high-carbon steels.

Horsepower calculations for screw conveyors are well standardized; however, each manufacturer has grouped numerical contents in a different fashion on the basis of individual design variation. Thus, in comparing horsepower requirements, it is advisable to use a specific formula for specific equipment. The typical feed arrangements for heavy or lumpy material

Table 5.4-29. EPRI LIME FGD SYSTEM DATA BOOK BELT CONVEYOR SPECIFICATIONS



SHEET 1 OF ______

CHECKED BY ______ DATE ______

SPEC. NO. ______

COMPUTED BY ______ DATE ______

PROJ. NO. ______

COMPANY ______ LOCATION ______

EQUIPMENT NO. ______ FOR USE ON ______ TOTAL NO. REQ'D. ______

SUPPLIER ______ P.O. NO. ______ PRICE EACH $ ______

	DUTY		ACCESSORIES
1	CONVEYOR LGTH. LIFT	20	SKIRTBOARDS: LGTH.
2	TPH: AVE. SURGE DESIGN	21	WALKWAY: WIDTH TYPE
3	HOW LOADED:	22	DECKING HANDRAILS
4	ANGLE TO DIRECTION OF BELT TRAVEL	23	COVER (TYPE)
5	HOURS/DAY	24	
6	NO. OF LOADING PTS.	25	
7	INSTALLATION: OUTDOOR ☐ INDOOR ☐	26	GUARD
8	OPERATION: CONTINUOUS ☐ INTERM'T. ☐	27	HOLDBACK: BAND, RATCHET
	FEED DESCRIPTION	28	HOLDBACK LOCATION
9	NAME	29	
10	DENSITY LB./CU. FT.	30	STRINGERS: WIRE ROPE, CHANNEL
11	MOISTURE	31	TRUSS, DECKPLATE
12	TEMP. °F. LUMPS °F. FINES °F.	32	BELT WIPER: BRUSH, WIRE, SPRAY
13	SIZE:	33	BLADE (SINGLE, DUPLEX, QUAD.)
14	MAX. LUMP % OF FEED	34	TAKE-UP: TRAVEL
15	CHARACTERISTICS:	35	SCREW, GRAVITY, SPRING
16	STICKY	36	VERTICAL, HORIZONTAL
17	CORROSIVE	37	DRIVE: V-BELT, CHAIN, SHAFT-MOUNTED
18	ABRASIVE	38	MOTOR TYPE:
19	ANGLE OF REPOSE	39	HP RPM V. PH. CY.

	DESCRIPTION							
40	BELT: WIDTH LGTH. SPEED IN F.P.M.				____ PLY ____ X ____ COVERS			
41	MAT'L. GRADE FINISH				OZ.			
42	BREAKER STRIP: YES ☐ NO ☐ TYPE OF SPLICE							
43	IDLER: TYPE	TROUGHERS	RETURNS	IMPACTS	TROUGH TRAINERS	RETURN TRAINERS		
44	DIA.							
45	SPACING							
46	BEARING							
47	LUBE.							
48	PULLEY: TYPE	HEAD	TAIL	SNUB	BEND	TAKE-UP		
49	MAT'L.							
50	DIA.							
51	LGTH.							
52	CROWN							
53	LAGGING							
54	HUBS							
55	BRGS.							

include rack-and-pinion, bin, and side inlet gates. Typical discharge arrangements include open-end trough, discharge trough end, and rack-and-pinion side gates.

Table 5.4-30 is a typical engineering data sheet for a screw conveyor.

5.4.33 Pond Water Return Pump

In systems that do not incorporate a thickener, or that do not produce a 50 to 60 percent solids sludge that can be ponded or landfilled, excess water from the sludge pond must be recycled to the scrubbing system. Water recycling is required to make the system a closed loop. Large sludge ponds separate out suspended solids and allow reactions to go to completion. The pH in the sludge pond rarely changes. The following factors should be considered when specifying the pond water return pump:

1. Erosion
2. Corrosion
3. Pump seals
4. Pump placement

5.4.33.1 Erosion--

With good pond design there should be few solids in the pond return water; however, reliability of return water pumps can be improved by accomodating some suspended solids.

5.4.33.2 Corrosion--

The pump should be designed to take a pH range of 6.5 to 9. Since chloride levels are usually higher in closed-loop systems, the pump should be chloride resistant. This will be true for all pumps, if closed-loop operations are specified and if it can be determined that chloride levels will be high. This corrosion is perhaps best deterred by using rubber (natural or synthetic) liners.

5.4.33.3 Pump Seals--

Since the pump will occasionally handle solids, water seals should be used instead of mechanical seals. Seal water should be controlled with an independent regulator and alarm for each pump.

5.4.33.4 Pump Placement--

The pond water return pump should be placed so that the water has traveled as far as possible from its point of entry to the pond. As a consequence, the desired precipitation reactions will occur and as many solids as possible will settle out.

Table 5.4-31 is a typical specification to be completed by the utility, architect/engineer, or equipment supplier for the pump vendor.

Table 5.4-30. EPRI LIME FGD SYSTEM DATA BOOK SCREW CONVEYOR SPECIFICATIONS

SHEET 1 OF ____
SPEC. NO. ____
PROJ. NO. ____

CHECKED BY ____ DATE ____
COMPUTED BY ____ DATE ____
COMPANY ____ LOCATION ____
EQUIPMENT NO. ____ FOR USE ON ____ TOTAL NO. REQ'D. ____
SUPPLIER ____ P. O. NO. ____ PRICE EACH $ ____

	DUTY
1	CONVEYING LENGTH LIFT
2	T.P.H. AVERAGE SURGE
3	HOURS PER DAY
4	NO. LOADING POINTS
5	NO. DISCHARGE POINTS
6	INSTALLATION: INDOOR ☐ OUTDOOR ☐
7	OPERATION: CONTINUOUS ☐ INTERMITTENT ☐
8	HOW LOADED:
9	
10	
	FEED DESCRIPTION
11	NAME OF MAT'L.
12	
13	DENSITY: LB. PER CU. FT.
14	MOISTURE (SURFACE) %
15	TEMPERATURE °F.
16	SIZE: x
17	MAX. LUMP: x % FEED
18	ANGLE OF REPOSE:
19	STICKY ☐ CORROSIVE ☐ FRIABLE ☐
20	ABRASIVE ☐ CONTAMINABLE ☐
21	HYGROSCOPIC ☐
	OPERATING CHARACTERISTICS
22	SIZE SCREW DIA.
23	SPEED: RPM
24	TROUGH LOADING: 15% ☐ 30% ☐ 45% ☐
25	LEFT ☐ RIGHT ☐ HAND CONVEYOR
26	DUST TIGHT ☐ WATER TIGHT ☐ OPEN ☐
27	
28	
	ELECTRICAL DATA
29	POWER: V. PH. CY.
30	MOTOR: HP DRIP-PROOF ☐
31	EXPL. PROOF ☐ TENV ☐ TEFC ☐
32	

	CONSTRUCTION
33	TROUGH: FLANGED ☐ DUST SEAL ☐
34	DROP BOTTOM ☐ FLARED ☐ TUBULAR ☐
35	JACKETED ☐ CI ☐ CS ☐ OTHER ☐
36	COVER: FLANGED ☐ SEMI-FLANGED ☐
37	DUST SEAL ☐ SNAP-ON ☐ BOLTED ☐
38	SCREW: THICKNESS
39	HELICOID ☐ SECTIONAL ☐ RIBBON ☐
40	CUT FLIGHTS ☐ MIXING PADDLES ☐
41	CI ☐ CS ☐ OTHER ☐
42	PITCH: STD. ☐ LONG ☐ SHORT ☐
43	DOUBLE FLIGHT ☐ TAPERED ☐
44	BEARINGS: ROLLER ☐ BALL ☐ SLEEVE ☐
45	
46	
	MATERIALS OF CONSTRUCTION
47	HANGER BRG.
48	THRUST BRG. END BRG.
49	COUPLINGS BOLTS
50	END PLATES
51	
52	
	DRIVE PREFERRED
53	SCREW CONV. REDUCER ☐
54	FLOOR MOUNTED REDUCER ☐
55	SHAFT MOUNTED REDUCER ☐
56	V-BELT ☐ CHAIN ☐ VARIABLE ☐
57	GUARD: YES ☐ NO ☐
58	
	NOTES:

Table 5.4-31. EPRI LIME FGD SYSTEM DATA BOOK
POND WATER RETURN PUMP SPECIFICATIONS

COMPANY
LOCATION
EQUIPMENT NO.
FOR USE ON
TOTAL NO. REQUIRED
SUPPLIER
P.O. NO.
PRICE EACH $

GENERAL INFORMATION

TYPE
DUTY: CONTINUOUS
INTERMITTENT
SERVICE

PROCESS INFORMATION

LIQUID:
DESIGN FLOW: NORMAL
MAX
GPM
PUMPING TEMPERATURE °F
SP. GR. @ PUMPING TEMPERATURE
VISCOSITY @ PUMPING TEMPERATURE
VAPOR PRESS. @ PUMP TEMP. (FT.LIQ.)
PH VALUE
CORROSIVE MATERIAL
SOLIDS (MAX. DIA.)

HYDRAULIC INFORMATION ___ FT. LIQ.

SUCTION PRESS. ABOVE LIQ. (ABS.) (+)
STATIC SUCTION LIFT (-): HEAD (+)
SUCTION FRICTION HEAD (-)
TOTAL SUCTION HEAD (17+18+19)
STATIC DISCHARGE HEAD
DISCHARGE FRICTION HEAD
DISCHARGE PRESS. ABOVE LIQ. (ABS.)
TOTAL DISCHARGE HEAD (21+22+23)
TOTAL DYNAMIC HEAD (24-20)
NPSH AVAILABLE (20-13)
NPSH REQUIRED

PUMP

MANUFACTURER
RPM
PERFORMANCE CURVE
SERIAL NO.
BPH @ SERVICE CONDITIONS
@ MAX. FLOW FOR IMPELLER
ROTATION @ DRIVE SHAFT END
COPIES REQUIRED OF:
PERFORMANCE CURVES
DIMENSION DRWGS.
OPERATING AND MAINTENANCE INSTRUCTIONS

MATERIALS

MATERIAL CODE - EXTERNAL CASING
INTERNAL PARTS

I - CAST IRON	INTERNALS CODE	I	B	S	C
B - BRONZE	IMPELLER	I	B	S	C
S - STEEL	INNER CASE PARTS	I	B	S	C
C - 11-13% CHROME	SLEEVE (PACKED)	Ch	Ch	Af	Af
A - ALLOY	SLEEVE (SEAL)	C	C	C	C
h - HARDENED	WEAR RINGS		B	Ch	Ch
f - FACED	SHAFT	S	S	S	S
	LANTERN RING				
	PACKING GLAND				

SUCTION CONN: SIZE
POSITION
DISCHARGE CONN: SIZE
POSITION
CONN. RATING
TYPE
PACKING TYPE
LANTERN RINGS
MATERIAL
COOLING
BEARINGS: TYPE
GREASE
OIL
IMPELLER: TYPE
SIZE FUR.
MAX.
VENT CONN:
DRAIN CONN.

FLUSHING CONNECTION:

DRIVER

FURNISHED WITH PUMP
BY OTHERS
TYPE:
FRAME:
MANUFACTURER:
ENCLOSURE
VOLTS
PHASE
CYCLE
HP
RPM
BEARINGS
LUBRICATION
COUPLING GUARD

NOTES:

5.4.34 pH Sensors and Controller

The pH value of a sample solution is proportional to the potential difference between a sensing electrode and a reference electrode that contains a small chemical battery with a liquid salt bridge conductor. When the pH probe is immersed in the sample solution, the electric impulse from the potential difference is amplified by a high impedance circuit. This signal is used as the input to a controller that changes the lime feed rate.

Controllers are either pneumatic or electronic; the latter has less lag time, hence the operation is slightly faster. The controller should be a three-mode instrument incorporating proportional, integral, and derivative modes. A standard controller is linear and the neutralization of an alkali is a nonlinear process. To obtain a dependable pH reading, multiple controllers or nonlinear controllers should be used. A nonlinear controller has recently been developed specifically for pH control. It permits small variations in pH value with little change in lime feed rate and provides proportionately larger changes in lime flow when pH exceeds present limits.

The following factors should be considered in the design and specification of a pH sensor and controller:

1. Probe location and maintenance
2. Probe type
3. Nonlinear control

5.4.34.1 Probe Location--

In many existing systems, improper design limits access to the pH sensors, which causes inadequate service. The pH sensors in lime scrubber service need frequent cleaning, because deposits can form on the electrode. This deposit insulates the electrode and prevents development of an accurate electrode potential. A properly designed electrode station should have easy access for pH sensor maintenance. If possible, each pH sensor should have a maintenance station equipped with a workbench, a cabinet to hold spare parts, small tools, and standardizing solutions.

5.4.34.2 Probe Type--

There are two types of pH sensors currently in use in lime scrubbing applications: dip-type and flow through. The dip-type pH monitor has been shown to offer more reliable operations and is being specified at new installations.

Flow-through electrodes should not be mounted directly in the process stream, but on a slipstream with block valves on each side for easy maintenance. Care must be taken to ensure adequate flow through the slipstream so that accurate readings can be obtained. At each probe location, pH sensors should be installed parallel for good maintenance and consistent readings. All amplifiers and calibration controls should be installed at the electrode station to permit one man to perform maintenance and adjustments.

The new pressurized "nonflowing" reference electrode, made of unbreakable plastic, is better suited for lime scrubber application than the older "flowing type" electrode of fragile glass construction. Miniaturized electronic packages that allow easy service and replacement are now available. In every probe, the wiring between the electrodes and the preamplifier should be as short as possible to prevent short-circuiting. In some models, the preamplifier is mounted in the electrode housing. Most of these instruments have either voltage or current output signals that are adjustable for both range and span.

To remove scale formation, electrodes can be equipped with ultrasonic cleaning devices. These devices are effective in removing mild scale deposits.

5.4.34.3 Nonlinear Control--

With the advent of nonlinear controllers for pH sensors, pH control has been less of a "hit or miss" situation. If possible, nonlinear controllers should be used. Table 5.4-32 is a specification for a pH control system to be completed by the utility, architect/engineer, or equipment supplier for the pH sensor vendor.

5.4.35 Level Controllers

Controls in a lime scrubber serve two functions: to feed makeup water into the system, and to control the levels in the various hold tanks. Dependability, not accuracy, is the goal for level control in the lime scrubbing system. The system should be supported by high- and low-level signals for notification of malfunction. Several controllers are available. Controllers using sensors that operate on the pneumatic bubble tube, mechanical flow, and ultrasonic principles are not suitable for lime scrubber applications because of the abrasive and chemical nature of the slurry. Displacement controllers and flange-mounted differential controllers are best suited for lime scrubber applications. Capacity level controllers are also effective.

5.4.35.1 Displacement Controllers--

This instrument is based on the principle that the weight of air in a cylinder containing liquid is proportional to the volume of liquid displaced by the submerged portion of the cylinder as the liquid falls and rises. An internal displacement transmitter is suitable when operating in an open-top tank,

Table 5.4-32. EPRI LIME FGD SYSTEM DATA BOOK
pH INSTRUMENTS SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO. ____________

COMPUTED BY ________ DATE ________ PROJ. NO. ____________

COMPANY ______________________________ LOCATION ______________________________

EQUIPMENT NO. ____________________ FOR USE ON ____________________ TOTAL NO. REQ'D. ________

SUPPLIER ____________________ P.O. NO. ____________________ PRICE EACH $ ________

	GENERAL		pH METER
1	RECORDER ☐ INDICATOR ☐ BLIND ☐	34	PLAIN ELECTRODE ☐ REFERENCE ELECTRODE ☐
2	CONTROLLER ☐ TRANSMITTER ☐	35	LENGTH:
3	CASE: CIRCULAR ☐ RECTANGULAR ☐	36	INSERTION LGTH. (IN.):
4	OTHER ☐	37	DIA. (IN.):
5	CASE COLOR: BLACK ☐ OTHER ☐	38	MATERIAL:
6	MOUNTING: FLUSH ☐ SURFACE ☐ YOKE ☐		ELECTRODE CONNECTIONS
7	NO. PTS. REC: IND.	39	FLANGE ☐ THD. ☐ CLAMP ☐ OTHER
8	CHART SIZE: 12" CIRC. ☐ OTHER ☐	40	BUSHING: 3/4" ☐ 1" ☐
9	CHART RANGE: NUMBER:	41	SANITARY: 3A ☐ OTHER
10	SCALE RANGE: TYPE:		CAPILLARY TUBING
11	CHART DRIVE: SPRING ☐ ELECTRIC ☐ PNEUM. ☐	42	LENGTH:
12	EXP PRF. ☐ V C AIR PR.	43	TYPE: ARMORED ☐ PLAIN ☐
13	CHART SPEED WIND	44	MATERIAL: CAPILLARY
14	MODEL NO.	45	ARMOR
	CONTROL	46	CONN. AT CASE: BACK ☐ BOTTOM ☐
15	TYPE: PNEUMATIC ☐ ELECTRIC ☐		INSTRUMENT CASE
16	OTHER ☐	47	MATERIAL: 304 S.S. ☐ 316 S.S. ☐ OTHER
17	MODE: PROP. ☐ RESET ☐ RATE ☐	48	CONSTRUCTION:
18	ON-OFF ☐ OTHER ☐	49	WELL: 3/4" ☐ 1" ☐ EXTERNAL ☐ INTERNAL ☐
19	OUTPUT: 3-15 PSI ☐ OTHER ☐	50	FLANGE:
20	ON MEASUREMENT INCREASE:	51	MODEL NO.
21	OUTPUT INCREASES ☐ DECREASES ☐		ACCESSORIES
22	ELEC. SW. TYPE - ON MEASUREMENT INCREASE:	52	FILTER & REGULATOR
23	CONTACTS OPEN ☐ CLOSE ☐	53	AIR SUPPLY GAGE
24	CONTACT RATING: AMPS VOLTS	54	LOCAL INDICATOR
	AUTO-MANUAL SWITCH	55	CHARTS & INKSET
25	NO. POSITIONS INTERNAL ☐ EXTERNAL ☐	56	MOUNTING YOKE
26	INTEGRAL ☐	57	PORTABLE CASE FEATURES
	SET-POINT ADJUSTMENTS	58	MTG. ACCESS.
27	MANUAL: INTERNAL ☐ EXTERNAL ☐	59	ALARM SWITCH
28	AUTO-SET: PNEUMATIC ☐ ELECTRIC ☐	60	HERMETICALLY SEALED ☐ EP ☐ GP ☐
29	BANK: FIXED ☐ ADJUSTABLE ☐	61	
30		62	
31	CLASS:	63	
32	IMPEDANCE		
33	pH-RANGE		

NOTES:

and it would be useful in such instruments as the thickener if the reaction tank were separate from the lime slurry storage tank. The instrument should be mounted from the top of the tank, and the cylinder suspended in a well or behind a baffle so that agitation in the tank does not affect the accuracy of the level controller. It gives dependable, trouble-free service if the slurry does not impinge on the instrument parts above the liquid level. Deposits in the tube or the air cylinder should be removed periodically.

5.4.35.2 Differential Controllers--

For closed-vessel applications, e.g., in a scrubber vessel, a differential pressure (DP) transmitter is best suited. This instrument measures the force necessary to hold a flexible metal diaphragm in a fixed position when one side is exposed to the liquid pressure below the liquid surface. Flange-mounted DP transmitters are suitable for scrubber application. The diaphragm is mounted in the end of a 4-in. stainless steel cylinder that extends through a nozzle into the chamber where the level is. A plastic-coated diaphragm should be used in an abrasive slurry. In such installations, the scrubber has to be down in order to carry out maintenance on the DP transmitters, because they have no shutoff valves. However, a properly designed DP transmitter requires little maintenance. A good installation should have the following features: a nozzle located away from agitation to minimize scouring of the diaphragm; and a small-diameter pipe connected to the instrument via a vessel tap that is located well above the minimum liquid level, in order to balance the static pressure of the DP cell. The most common problem of DP transmitters is that the balancing line is either plugged with solids, or the line is filled with gas as a result of evaporation. For proper operation, the balancing line should be installed with a rotometer to purge the line with water, and a valve tap should be installed in the tank near and at the same elevation as the transmitter.

5.4.35.3 Capacitance Controllers--

For closed-tank application, capacitance controllers are effective though expensive. These instruments use an insulated electrical probe that measures the capacitance between the electrode and the grounded vessel. They are simply constructed, have no moving parts, and are accurate. The accuracy of the readings is unaffected by slurry deposits on an electrode or by the presence of scrubber agitations. The electrodes should not be placed at the axis of the tank.

Table 5.4-33 illustrates a typical specification for a level sensor as it would be prepared by a utility engineer for equipment vendors.

Table 5.4-33. EPRI LIME FGD SYSTEM DATA BOOK
LIQUID LEVEL INDICATOR SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO.________

COMPUTED BY ________ DATE ________ PROJ. NO.________

COMPANY ______________________________ LOCATION ________________

EQUIPMENT NO.______________ FOR USE ON ______________________ TOTAL NO. REQ'D.________

SUPPLIER ______________________ P.O. NO.______________________ PRICE EACH $ ________

	GENERAL		**ACTUATION**
1	LIQUID LEVEL RANGE:	33	SOURCE: INST. AIR ☐ PLANT AIR ☐ HAND PUMP ☐
2	TYPE: ISOLATING DIAPHRAGM ☐ DIP TUBE ☐	34	OTHER ☐
3	OTHER ☐	35	PRESSURE REQ'D.
4	MFR. & MODEL:	36	FLOW MODE: CONTINUOUS ☐ DURING READING ☐
5		37	FLOW RATE:
	TANK	38	FLOW CONTROL: VALVE ☐ DIF. RELAY ☐ NONE REQ'D. ☐
6	LOCATION: INDOORS ☐ OUTDOOR ☐	39	
7	CONNECTIONS: TOP ☐ SIDE ☐		**DIP TUBE**
8	WELDED ☐ BOLTED ☐	40	OVERALL LENGTH:
9	INTERNAL PRESS. VENTED TO ATM. ☐ PSI	41	DISTANCE-LOWEST OPENING TO TANK BOT.
10	MATERIAL WET BY PROCESS:	42	INACTIVE LENGTH AT LOWER END:
11		43	SIZE:
	SERVICE CONDITIONS	44	MATERIAL:
12	FLUID:	45	
13	WORK. PRESS. (MIN/NORM/MAX):		**ISOLATING DIAPHRAGM**
14	WORK. TEMP. (MIN/NORM/MAX):	46	NO. PER INDICATING POINT:
15	S.G. @ NORM. TEMP.	47	MTG. LOCATION: TOP ☐ BOTTOM ☐ SIDE ☐
16		48	TANK CONNECTION-TYPE & SIZE:
	INDICATOR	49	CONNECTION MAT'L.
17	TYPE: WELL MANO. ☐ U TUBE ☐ GAGE ☐	50	DIAPHRAGM MAT'L.
18	OTHER ☐	51	
19	SIZE:		**ACCESSORIES**
20	INDICATING FLUID - TYPE & S.G.	52	FLOW INDICATOR:
21	CONNECTIONS: VENTED TANK ☐ NON-VENTED ☐	53	HAND PUMP:
22	LOCATION: LOCAL ☐ SIDE ☐ TOP ☐	54	CHECK VALVE:
23	REMOTE ☐ SURFACE ☐ FLUSH ☐	55	INDICATOR MTG. BRACKETS:
24	INDOORS ☐ OUTDOORS ☐	56	CONNECTION TUBING:
25	AMBIENT TEMP. RANGE:	57	TANK FITTING:
26	DISTANCE FROM TANK:	58	PRESS. FITTING:
27	SCALE UNITS:	59	FILTER REGULATOR:
28	SCALE/PRESSURE RANGE:	60	DIFFERENTIAL RELAY:
29	SMALLEST SCALE DIVISION:	61	PACKING NUT & GLAND:
30	EMPHASIS/NUMERALS EACH: SCALE DIV.	62	
31	CASE TYPE:	63	
32	CASE MATERIAL:	64	

NOTES:

5.4.36 Flowmeters

In a lime scrubber, flow rates are usually measured on several streams. Lime feed flow rates are measured to allow pH control. Flow rate of slurry to the thickener is measured to improve the operation of the thickener. Several types of flowmeters can be used to measure flow. These include target meters, rotometers, or purge differential-pressure transmitters with venturi tubes or flow nozzles. These mechanical flowmeters are not suitable for the abrasive slurry encountered in lime scrubbers. The most acceptable devices to measure flow rates in lime scrubbers are electromagnetic flowmeters and nuclear density gauges. They have no operating parts in contact with the fluid, produce very little pressure drop, and are fairly accurate.

5.4.36.1 Magnetic Flowmeters--

These devices use electromagnetic induction to produce an AC voltage signal that is directly proportional to the flow rate of the liquid through the piping. They can normally be calibrated from zero to full range. This output signal is converted by signal converter for hookup to various readout and indicating instruments. A common arrangement is a panel-mounted indicating transmitter coupled with a strip chart recorder. An electronic indicating controller should be used in cases where the fluid must be controlled. To avoid constrictive flow and short meter life, flowmeters should be the same size as the pipe on which they are measuring the flow. Many materials are available for liners and electrodes. Polyurethane, neoprene, and synthetic rubber liners are best suited for scrubber applications. Stainless steel is the best material for electrodes. Some vendors offer field-replaceable electrodes only in polyurethane, neoprene, rubber, and lined meters. These electrodes can be replaced without the meter being taken out of the process stream. Among the accessories are ultrasonic electrode cleaners. A metering installation should have a vertically mounted flowmeter with upward fluid flow. The electrodes should be horizontal. The pipe should be full when the slurry is measured. To obtain accurate measurements, there should, if possible, be no air in the fluid stream. Good quality magnetic flowmeters give trouble-free performance; however, when selecting the vendor, the availability of startup personnel to inspect and calibrate the meter should be considered. Magnetic flowmeters come in sizes from 1/10 in. to 6 ft in diameter.

5.4.36.2 Nuclear Density Sensors--

Nuclear density meters use a nuclear source to emit gamma rays through a flowing stream. The density is proportional to the number and intensity of the gamma rays that pass through the fluid and the surrounding pipe. The main advantage of the nuclear density gauge is its ease of application. It can be applied directly to existing process piping without inserting anything into the pipe line. There is no wear on a liner, as happens in a nuclear density cell. Table 5.4-34 illustrates a typical flowmeter specification as it would be prepared by a utility engineer for the instrument vendor.

5.4.37 SO_2 Analyzers

Continuous monitoring of gaseous emissions can be performed by extractive or in situ analyzers. This section discusses both types, their advantages and disadvantages. A continuous monitoring system has three subsystems: sampling, analyzer, and data logging devices.

5.4.37.1 Extractive Analyzers--

These instruments have undergone greater development than the in situ class, since they apply a standard laboratory method for the analysis. The most common extractive analyzers use nondispersible infrared and ultraviolet absorption, chemiluminescence, fluorescence, and electrochemical techniques.

Several contaminants in the flue gas will interfere with the analytical method. Hence, the sample has to be processed by removing particulate matter, water vapor, and other contaminant gases. Filters, refrigerators, and pumps are used to condition the sample before the analysis. The following factors should be considered when specifying an extractive SO_2 analyzer.

1. Probe location and type
2. Sample line maintenance

5.4.37.2 Probe Locations--

The simplest method of extracting a sample with a representative concentration is to insert a probe in the source at a point where SO_2 is present. Compositional stratification, however, can lead to single-point measurement errors up to 15 percent. Therefore, the adequacy of single-point measurement should be verified. A multiple sample probe works by drawing equal volumes of samples through each port, mixing them within the probe body, and delivering an integrated gas sample through a single port.

5.4.37.3 Sample Line Maintenance--

The primary consideration in constructing a probe is particulate control. A filter at the probe inlet (perhaps 30 mesh) is typically used to remove the larger particulate matter. A moisture control system is in-line immediately preceding the sample chamber. Blowback air is used to clean the lines of any particulate matter that is deposited. Pumps, valves, and sampling lines should be made of 316 stainless steel or Teflon. Pumps are often the weak link of the sampling chain, developing

Table 5.4-34. EPRI LIME FGD SYSTEM DATA BOOK
FLOWMETER SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO. ______________
COMPUTED BY ________ DATE ________ PROJ. NO. ______________
COMPANY ______________________________ LOCATION ______________________________
EQUIPMENT NO. ________________ FOR USE ON ________________ TOTAL NO. REQ'D. ________
SUPPLIER ________________ P.O. NO. ________________ PRICE EACH $ ________

GENERAL			
1 ITEM NUMBER			
2 MODEL NUMBER			
3 LOCATION			
4 TYPE INSTRUMENT			
SERVICE CONDITIONS			
5 FLUID			
6 CONDITION			
7 MAX. FLOW/NORMAL FLOW			
8 OPERATING PRESS. PSIG			
9 OPERATING TEMP. °F.			
10 SP. GR. AT 60°F./AT FLOW COND.			
11 VISCOSITY AT FLOW COND.			
12 CLARITY OF FLUID			
METER			
13 MATERIAL			
14 BODY			
15 FLOW TUBE			
16 ROTOR			
17 GASKET			
18 PICKUP COIL			
19 MAGNET			
20 INLET LOCATION			
21 OUTLET LOCATION			
22 MOUNTING			
23 TUBE TYPE AND NO.			
24 ROTOR TYPE AND NO.			
25 TUBE CALIBRATION			
26 SCALE LOCATION			
27			
28			
ACCESSORIES			
29			
30			
TRANSMITTER			
31 TYPE			
32 MODEL NUMBER			
33 BLIND OR INDICATOR			
34 MOUNTING			
35 CASE COLOR			
36 CONN. 1/4" NPT OTHER			
37 OUTPUT, PSIG			

leaks or becoming plugged. Diaphragm and metal bellows pumps have been used successfully upstream from the analyzers, whereas water or air aspirators have been used on the downstream side.

5.4.37.4 In Situ Analyzers--

In situ monitors have been specifically designed to overcome many of the problems encountered in extractive analyzers. These instruments use electro-optical techniques based on infrared or ultraviolet absorption. The monitors are placed across a stack, or have a probe placed in a stack, and perform the analysis on the gas without any sample modification. The instruments generally consist of either a long-slotted probe with a mirror on one end, or a reflector and analyzer placed on opposite sides of the stack. Air curtains are used to prevent particulate matter from covering the instrument mirrors or windows located in the stack.

In situ analyzers have the advantage of continually scanning an entire cross section of stack gases and thus reading a truly average concentration. In addition, in situ monitors require no sample extraction or conditioning system and thus eliminate possible sample interactions.

In situ monitors, however, have some basic design disadvantages.

1. They are limited to the monitoring of only one stack at a time, whereas extractive systems may draw samples from a number of sites.

2. In situ monitors are limited in their location and are often exposed to extremes in weather conditions and to harsh environments. They may be difficult to reach for repairs.

Table 5.4-35 is a typical data sheet for an extractive or in situ SO_2 analyzer.

5.4.38 Pressure Sensors and Controller

Three types of devices may be used to measure process pressure: 1) manometers, 2) electrical elements, and 3) electrical sensing devices. In a lime FGD system, pressure gauges are commonly used to measure pressure drop across the scrubber absorber and mist eliminator.

Table 5.4-36 is a typical data sheet for a pressure control system.

Table 5.4-35. EPRI LIME FGD SYSTEM DATA BOOK
SO_2 ANALYZER SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO. ________
COMPUTED BY ________ DATE ________ PROJ. NO. ________
COMPANY ________ LOCATION ________
EQUIPMENT NO. ________ FOR USE ON ________ TOTAL NO. REQ'D. ________
SUPPLIER ________ P.O. NO. ________ PRICE EACH $ ________

1	GENERAL INFORMATION	
2		
	PROCESS INFORMATION	
3	LOCATION	STATIC PRESSURE IN. WG.
4	GAS	ACFM, MAX. AT °F
5	TYPICAL GAS COMPOSITION(%): SO_2,	O_2, CO_2, NO_x,
	EXTRACTIVE ANALYZER	IN SITU ANALYZER
6	PROBE: TYPE SIZE	PROBE: TYPE SIZE
7	MATL.:	MATL.:
8	FILTER: TYPE SIZE	MIRROR: TYPE SIZE
9	MATL.:	MATL.:
10	CONDENSER: TYPE SIZE	BLOWER: TYPE RATING
11	MATL.:	MATL.:
12	FINE FILTER: TYPE SIZE	FILTER: TYPE SIZE
13	MATL.:	MATL.:
14	PUMP: TYPE SIZE	GRATING: TYPE SIZE
15	MATL.:	MATL.:
16	SAMPLE LINE: SIZE MATL.	SAMPLE LINE: SIZE MATL.
17	AUTO BLOWBACK: YES NO	DETECTOR: YES☐ NO☐
18	ANALYSIS PRINCIPLES:	ANALYSIS PRINCIPLES:
19		
20		
21		

Table 5.4-36. EPRI LIME FGD SYSTEM DATA BOOK PRESSURE SENSORS SPECIFICATIONS

CHECKED BY ______ DATE ______ SPEC. NO. ________

COMPUTED BY ______ DATE ______ PROJ. NO. ________

COMPANY ______________________ LOCATION ______________________

EQUIPMENT NO. __________ FOR USE ON ______________________ TOTAL NO. REQ'D. ________

SUPPLIER ______________________ P.O. NO. ______________ PRICE EACH $ ________

	GENERAL INFORMATION
1	DESCRIPTION RECORDER ☐ INDICATOR ☐ BLIND ☐
	CONTROLLER ☐ TRANSMITTER ☐
2	CASE RECTANGULAR ☐ CIRCULAR ☐
	OTHER
3	CASE COLOR BLACK ☐ OTHER
4	MOUNTING FLUSH ☐ SURFACE ☐ YOKE ☐
5	NO. PTS. RECORDING INDICATING
6	CHART YP 12" CIRC. ☐ OTHER
7	CHART RANGE NUMBER
8	SCALE RANGE TYPE
9	CHART DRIVE SPRING ☐ ELECTRIC ☐ PNEU. ☐
10	CHART SPEED WIND (DAYS)
11	VOLTS/CYCLES EX. PRF. ☐
12	AIR PRESS.
	TRANSMITTER
13	TYPE PNEUMATIC ☐ ELECTRIC ☐
14	OUTPUT 3-15 PSI ☐ OTHERS
15	RECEIVERS ON SHEET NO.
	CONTROL
16	TYPE PNEUMATIC ☐ ELECTRIC ☐
	OTHER
17	PROP % AUTO-RESET ☐ RATE ACTION ☐ ON-OFF ☐
	OTHER
18	OUTPU 3-15 PSI ☐ OTHER
19	ON MEASUREMENT INCREASE:
	OUTPUT INCREASES ☐ DECREASES ☐
	AUTO MANUAL SWITCH
20	NO. POSITIONS EXTERNAL ☐ INTERNAL ☐
	INTERNAL ☐
	SETPOINT ADJUSTMENTS
21	MANUAL INTERNAL ☐ EXTERNAL ☐
22	AUTO-SET PNEUMATIC ☐ ELECTRIC ☐
23	BAIK FIXED ☐ ADJUSTABLE ☐
24	OTHERS

	PRESSURE ELEMENT
25	SPIRAL ☐ BELLOWS ☐ BOURDON ☐
	DIAPHRAGM ☐ HELICAL ☐
	OTHER
	MATERIAL
26	BRONZE ☐ STAINLESS ☐ STEEL ☐
	OTHER
27	ABSOLUTE PRESS. COMPENSATION
28	STATIC HEAD COMPENSATION
	HEAD
29	RANGE
	PSIG ☐ IN.HG.VAC. ☐ PSIA ☐
	OTHER
30	CONNECTION-NPT 1/4" ☐ 1/2" ☐
	BACK ☐ BOTTOM ☐ OTHER
	ACCESSORIES
31	FILTER & REGULATOR
32	AIR SUPPLY GAUGE
33	LOCAL INDICATOR
34	CHARTS & INKSET
35	MOUNTING YOKE
36	PULSATION DAMPENER
37	SYPHON
38	ALARM SWITCH
	HERMETICALLY SEALED ☐ E.P ☐ G.P. ☐
	OPERATING CONDITIONS
	PRESSURE. NORMAL MAX.
	TEMPERATURE NORMAL MAX.
	FLUID
	SEAL FLUID S.G. @ 60°F.
	NOTES

5.4.39 Temperature Sensors and Controller

The most commonly used temperature measuring devices are thermocouples, resistance thermometers, liquid-in-glass thermometers, and pyrometers. In a lime FGD system, temperature sensors are installed at several points, including the scrubber inlet, absorber outlet, slakers, and recirculation tank.

Table 5.4-37 is a typical data sheet for an electrical temperature control system.

5.4.40 Control Valves

Control valves have been described in Section 3.4.3 (Control Modes). Butterfly or ball valves should not be used to control the flow of lime feed slurry, since they are susceptible to frequent plugging and jamming. The wedge should not be rubber coated because it can erode rapidly. Pinch valves are generally suitable for slurry flow control. This is a major problem area where considerable research is needed.

Table 5.4-38 is a typical data sheet for a control valve.

Table 5.4-37. EPRI LIME FGD SYSTEM DATA BOOK
TEMPERATURE SENSORS AND CONTROLLERS SPECIFICATIONS

CHECKED BY ________ DATE ________ SPEC. NO. ________

COMPUTED BY ________ DATE ________ PROJ. NO. ________

COMPANY ________________ LOCATION ________________

EQUIPMENT NO. ________ FOR USE ON ________________ TOTAL NO. REQ'D. ________

SUPPLIER ________________ P.O. NO. ________________ PRICE EACH $ ________

	GENERAL		CONTROL
1	DESCRIPTION: RECORDER ☐ INDICATOR ☐	32	TYPE: PNEUMATIC ☐ ELECTRIC ☐
2	CONTROLLER ☐ TRANSMITTER ☐ OTHER ☐	33	OUTPUT:
3	MFR. & MODEL:	34	MODE: PROPORTIONAL ☐ RESET ☐ RATE ☐
4	CASE. RECTANGULAR ☐ CIRCULAR ☐	35	ON-OFF ☐
5	COLOR: CASE DIAL	36	ON MEASUREMENT INCREASE -
6	MOUNTING: FLUSH ☐ SURFACE ☐	37	OUTPUT: INCREASES ☐ DECREASES ☐
7	NO. OF POINTS:	38	CONTACTS: OPEN ☐ CLOSE ☐
8	INDICATOR: ANALOG ☐ DIGITAL ☐	39	CONTACT RATING: AMPS.@ VOLTS
9	HORIZ. ☐ VERT. ☐		SET POINT ADJUSTMENT
10	CHART TYPE: IN. STRIP ☐ IN. CIRCLE ☐	40	MANUAL: INTERNAL ☐ EXTERNAL ☐
11	CHART RANGE: NUMBER:	41	AUTO-SET: PNEUMATIC ☐ ELECTRICAL ☐
12	SCALE RANGE: TYPE:	42	BAND: FIXED ☐ ADJUSTABLE ☐
13	CHART SPEED: REV./DAY IN./HR.	43	
14			ACCESSORIES
15	PEN SPEED: SECONDS FULL SCALE TRAVEL	44	AUTO MANUAL SWITCH: POSITIONS
16	PRINT SPEED: SECONDS PER POINT	45	INTERNAL ☐ EXTERNAL ☐ INTEGRAL ☐
17	BALANCING: MANUAL ☐ AUTOMATIC ☐	46	ALARM CONTACTS:
18	STANDARDIZATION: MANUAL ☐ AUTOMATIC ☐	47	
19		48	CHARTS & INKSET:
20	CHART DRIVE: VOLTS CYCLES	49	
21	INPUT IMPEDANCE: OHMS MIN. OHMS AT BAL.	50	FILTER & REGULATOR:
22	INSTRUMENT ERROR LIMIT:	51	
23	LOCATION: INSIDE ☐ OUTSIDE ☐ HAZARDOUS ☐	52	AIR SUPPLY GAGE:
24	AMBIENT TEMP. RANGE:	53	LOCAL INDICATOR:
25		54	
	SENSING ELEMENT	55	
26	FORM: THERMOCOUPLE ☐ RESISTANCE ☐	56	
27	OTHER ☐		NOTES:
28	MATERIAL OR CALIBRATION:		
29	REF. JUNCTION COMPENSATION: YES ☐ NO ☐		
30	STD. LIMIT OF ERROR:		
31	SENSOR IS: ISOLATED ☐ GROUNDED ☐		
REMARKS:			

Reproduced from best available copy.

Table 5.4-38. EPRI LIME FGD SYSTEM DATA BOOK
CONTROL VALVE SPECIFICATIONS

SPEC. NO. ________
PROJ. NO. ________
CHECKED BY ________ DATE ________
COMPUTED BY ________ DATE ________
COMPANY ________________________ LOCATION ________________________
EQUIPMENT NO. ____________ FOR USE ON ____________________ TOTAL NO. REQ'D. ________
SUPPLIER ________________________ P.O. NO. ____________ PRICE EACH $________

	GENERAL
1	DESCRIPTION: PRESS. ☐ TEMP. ☐ FLOW ☐
2	LEVEL ☐ OTHER ☐
3	TYPE: GLOBE ☐ BUTTERFLY ☐ BALL ☐
4	OTHER ☐
5	MFR. & MODEL:
	VALVE BODY
6	FORM: STRAIGHT ☐ ANGLE ☐
7	OTHER ☐
8	SIZE:
9	TYPE: CAST ☐ BARSTOCK ☐
10	OTHER ☐
11	ENDS: SCREWED ☐ FLANGED ☐ FLANGELESS ☐
12	TYPE & SIZE
13	PRESS/TEMP RATING: PSIG @ °F
14	BONNET: STD. ☐ OTHER ☐
	INNER VALVE
15	CHARACTERISTIC: EQ. % ☐ LINEAR ☐ QUICK OPEN ☐
16	OTHER ☐
17	PLUG FORM:
18	NO. OF PORTS & SIZE:
19	TRIM: FULL SIZE ☐ RESTRICTED ☐
20	PLUG TRAVEL:
21	GUIDING: TOP & BOT. ☐ TOP ☐ PORT ☐
22	OTHER ☐
	MATERIALS
23	VALVE BODY: BRONZE ☐ CARB. STL. ☐ ___ SS ☐
24	OTHER ☐
25	TRIM-PLUG: 316 SS ☐ OTHER ☐
26	SEAT: 316 SS ☐ OTHER ☐
27	SPRING: 316 SS ☐ OTHER ☐
28	PACKING: TEFLON ☐ OTHER ☐
29	DIAPHRAGM: BUNA-NYLON ☐ OTHER ☐

	VALVE ACTUATOR
30	TYPE: PNEUMATIC ☐ ELECTRIC ☐
31	OTHER ☐
32	DIAPHRAGM ☐ PISTON ☐
33	OTHER ☐
34	SIGNAL LEVEL:
35	AIR TO: CLOSE ☐ OPEN ☐
36	FAILURE POS. OPEN ☐ UNCHANGED ☐ CLOSED ☐
	SERVICE CONDITIONS
37	FLUID
38	TEMPERATURE: NORM °F MAX. °F
39	INLET PRESSURE: NORM. PSIG, MAX. PSIG
40	MAX. PRESS.DROP THRU VALVE:
41	S.G.: @ 60°F @ F.T.
42	VISCOSITY @ F.T.
43	MIN. FLOW: ΔP: Cv:
44	MAX. FLOW: ΔP: Cv:
45	NORM. FLOW: ΔP: Cv:
	ACCESSORIES
46	POSITIONER
47	SOLENOID VALVE
48	FILTER REGULATOR
49	LIMIT SWITCHES
50	LUBRICATOR ☐ ISOLATOR VALVE ☐
51	
52	
53	
	NOTES —

REMARKS -

5.5 BID EVALUATION

Economics is a key element in the evaluation of bids. The utility or architect-engineering (A-E) firm that is deciding among proposed systems will have to assess various capital and operating costs, and it will frequently find it hard to make comparisons. It is easy to imagine a situation where System A needs a lower capital investment than System B, but System B needs lower annual operating and maintenance (O&M) expenditures than System A. In these cases, it is necessary to investigate the overall economic impact of the system.

The utility will not actually make an initial expenditure in the amount of the overall capital cost. Circumstances will vary among utilities, but in general, funds in the amount of the overall capital cost will be borrowed and paid back within the course of 15 to 20 years.

The best economic analysis is probably one that compares "present-worth" or "present-value." This methodology reduces all future economic differences among the various systems to a single equivalent present amount. To work properly, the method must rest upon accurate forecasts of operating costs. Every effort should be made to obtain these forecasts from the various equipment suppliers.

The evaluation team will have to factor the costs for plant life and load factor through the projected years of operation. As the plant ages, load factor will decrease and operating costs (expressed in current dollars) will, therefore, be reduced. For details on the "present-worth" analysis, the reader may consult an economic decision-making text, such as Process Plant Estimating, Evaluation, and Control by K.M. Guthrie.

Tables 5.5-1 through 5.5-8 present "spread sheets" useful for evaluating bids for the following eight major equipment items used in a lime slurry FGD system:

- Slaker
- Lime slurry pump (With minor modifications, this sheet could be used for any pump in the system. The thickener underflow pump and flocculant proportioning pump sheets will need the most modifications.)
- SO_2 absorber
- Mist eliminator

Table 5.5-1. BID EVALUATION FOR SLAKERS

Characteristics	Vendor 1	Vendor 2	(others as needed)
Design Performance			
Lime feed, lb/h			
Total water required, gal/min			
Residence time, min			
Slaker size, ft			
Lime slurry			
Flow, gal/min			
Solids, wt.%			
pH			
Temp., °F			
Number of slakers			
Agitator			
Type/rpm			
Size			
Drive: type			
Motor			
hp/rpm			
Capital cost, $			
Slakers			
Agitator			
Motor			
Subtotal			

Table 5.5-2. LIME SLURRY PUMP

Characteristics	Vendor 1	Vendor 2	(others as needed)
Pump performance			
Pump selection			
Pump size			
Efficiency, %			
Pump speed, rpm			
BHP @ design			
BHP installed			
Material of construction			
Lining			
Casing			
Impeller			
Shaft			
Wear rings			
Cost, $			
Pump			
Coupling			
Motor			
Subtotal			

Table 5.5-3. BID EVALUATION FOR SO_2 ABSORBER

Characteristics	Vendor 1	Vendor 2	(others as needed)
Design performance			
Internal configuration			
Size			
No. of stages of absorption			
Gas flow, °F			
Inlet			
Outlet			
SO_2 removal efficiency, %			
Pressure drop, in. WG			
Turndown ratio			
Max L/G, gal/1000 acf			
Operating L/G			
Materials of construction			
Shell			
Linear			
Abrasion zones			
Stagnant zones			
Internals			
Packing, if any			
Nozzles			
Capital cost, $			
Absorber			

Table 5.5-4. BID EVALUATION FOR MIST ELIMINATOR

Characteristics	Vendor 1	Vendor 2	(others as needed)
Design performance			
Gas flow, acfm @ °F			
Mist			
Inlet, gr/scf			
Outlet, gr/scf			
Gas velocity			
Mist eliminator			
Type/shape			
No. of passes/stages			
Vane spacing, in.			
Freeboard distance, ft			
Material of construction			
Mist eliminator			
Wash water headers			
Wash water spray nozzles			
Wash water collectors			
Wash water system pump			
Water flow, gal/min			
Pressure, psig			
Pump speed, rpm/bph			
Design installed			
Motor, hp/rpm			
Capital cost, $			
Mist eliminator			
Wash water headers/ sprays/collectors			
Wash water pump			
Subtotal			

Table 5.5-5. BID EVALUATION FOR REHEATER

Characteristics	Vendor 1	Vendor 2	(others as needed)
Design Performance			
Reheat			
°F			
Btu/h			
Direct/indirect			
Gas flow, acfm @ °F			
SO_2/moisture, ppm/vol.%			
Fuel/heating medium flow, lb/h			
Overall heat Transfer coefficient, Btu/h-ft^2 °F			
Tube bundle			
No. of tubes			
No. of runs			
Support			
Material of construction			
Tubes			
Baffles			
Supports			
Fuel heating medium pump			
Speed, rpm/bhp, design			
Drive: type/rpm installed			
Motor			
hp/rpm			
Capital cost, $			
Tube bundle			
Pump			
Subtotal			

Table 5.5-6. BID EVALUATION FOR BOOSTER FAN

Characteristics	Vendor 1	Vendor 2	(others as needed)
Design performance			
Fan selection			
Fan size			
Fan hp, design			
Fan hp, installed			
Air flow through fan, acfm			
Temperature, °F			
Fan speed, rpm			
Pressure increment, in. WG			
Materials of construction			
Housing			
Blades			
Bearing			
Shaft			
Capital Cost, $			
Fan			
Motor			
Subtotal			

Table 5.5-7. BID EVALUATION FOR RECIRCULATION TANK

Characteristics	Vendor 1	Vendor 2	(others as needed)
Design performance			
Tank size, ft/shell thk, in.			
Tank capacity, gal			
Slurry height, ft			
Lime slurry,			
Residence time, min			
Temperature, °F			
pH			
Operating pressure, psig			
Wt. of absorber, tons			
No. of recirculation tanks			
Material of Construction			
Shell/lining			
Supports			
Agitator			
Baffler			
Agitator			
Type/rpm			
Size/nos.			
Drive types			
Motor, hp/rpm			
Capital cost, $			
Recirculation tank			
Supports			
Agitator			
Absorber			
Subtotal			

Table 5.5-8. BID EVALUATION FOR THICKENER

Characteristics	Vendor 1	Vendor 2	(others as needed)
Design performance			
Settling, ton/ft^2/day			
Desired			
Maximum			
Size			
Capacity, gal			
Underflow, gal/min			
% solids			
Overflow, gal/min			
Lifting mechanism			
Rake type			
Torque limit			
Materials of construction			
Tank shell			
Rake coating			
Rake metal			
Support stanchion			
Motor			
Type			
hp			
Cost, $			
Tank			
Rake			
Subtotal			

- Reheater
- Booster fan
- Absorber recirculation tank
- Thickener

These sheets list major design information, materials of construction, and costs submitted by the various bidders for each item. This comparative strategy enables the utility to select the best system.

To obtain useful estimates of operating costs, the utility or A-E firm will have to provide the costs of items such as electricity, water, fuel for reheat, and steam. The equipment suppliers should also be provided with normal design operating levels so that the operating costs will all refer to similar load conditions.

It is also reasonable to ask for guidelines for maintenance costs. These figures will probably be expressed in the form of a percentage of the overall capital cost. The vendors should be asked to document those projected maintenance charges.

GLOSSARY

Following is a guide to the terminology, abbreviations, and assumptions used in this text.

acfm - actual cubic feet per minute; a gas flow rate, expressed with respect to operating conditions (temperature and pressure).

Abrasion - the deterioration of a material surface by mechanical means.

Absorption - the process by which gas molecules are transferred to a liquid phase by scrubbing.

Adsorption - the process by which gas molecules are removed from a gas stream by means of adhesion to the surface of a solid.

Availability factor - ratio of hours an FGD system was "accessible" for operation to the hours in the time period (regardless of actual operation time), expressed as a percentage.

British thermal unit - the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit.

Centrifugal separation - the separation of phases in a composite fluid stream by applying a circular motion to the stream and forcing the higher density component to the outside wall of the device, where it is collected.

Clarifier - a continuous settling basin used in wastewater treatment applications, producing a clear overflow and a concentrated sludge from the bottom.

Cocurrent flow - circulation in the same direction of two streams through a piece of equipment.

Condenser - piece of equipment used to convert a vapor state to liquid state by compression or extraction of heat.

Corrosion - the deterioration of a metallic material by electrochemical attack.

Countercurrent flow - circulation in opposite directions of two streams through a piece of equipment.

Cyclone - a piece of air pollution hardware used for particulate removal by centrifugal separation.

ESP - electrostatic precipitator; an air pollution device used to remove particulates from an exhaust stream by initially charging them with an electrode and then collecting them on an oppositely charged plate.

Efficiency - ratio of the amount of a pollutant removed to the total amount introduced to the removal operation.

Entrainment - the suspension of liquid droplets or mist in a gas stream.

FGD - flue gas desulfurization; the process by which sulfur is removed from the combustion exhaust gas.

FD - forced draft; a fan, or blower, used to produce motion in an enclosed stream of gases by creating a positive pressure in the stream and pushing it.

Flooding - the situation in countercurrent gas-liquid operations when gas velocity is high enough to impede the flow of liquid through the tower; excessive entrainment.

Free space - voids within the packing material in a packed tower.

ID - induced draft; a fan used to move an enclosed stream of gases by creating a negative pressure in the stream and pulling it.

MW - megawatts; unit used to describe gross or net power generation of a particular facility. One watt equals one joule per second. One megawatt equals 10^6 watts.

Mist - dispersion of relatively large liquid particles in a gas stream; carryover from a gas-liquid contact operation.

Mist eliminator - a piece or section of pollution hardware used to remove a dispersion of liquid particles from a gas stream.

Nm^3/h - normal cubic meters per hour; unit of gas flow rate under the standard condition of 0°C and 760 mm Hg.

NSPS - New Source Performance Standards; environmental regulations that apply to a new installation.

Operability factor - ratio of hours an FGD system operated to hours of boiler operation during a particular time period, expressed as a percentage.

ppm - parts per million; units of concentration; in wastewater applications equal to milligrams per liter; in air pollution applications equal to moles of pollutant to million moles diluent.

Packed-bed scrubber - a piece of pollution equipment using small plastic or ceramic pieces, with high surface area-to-volume ratios, for intimate contact between liquid and gas for mass transfer of a pollutant.

Packed tower - a tower (usually cylindrical) used for pollutant removal by a packed scrubber. Untreated gas enters the bottom and travels upward, and liquid enters the top and travels downward.

Perforated tray scrubber - pollution control equipment that passes the untreated gas through holes in a series of plates on which liquid flows, causing an intimate contact between phases by breaking the gas flow into bubbles.

Pressure drop - the difference in force per unit area between two points in a fluid stream, due to resistance to the flow of that stream.

Redistributor - a device used to spread out the flow of liquid in a packed scrubber to insure uniform wetting of packing material.

Reliability factor - ratio of hours an FGD system operated to hours it was called on to operate, expressed as a percentage.

Residence time - the amount of time a unit volume of gas or liquid spends in a pollution control device.

scfm - standard cubic feet per minute; units of a gas flow rate at 60°F and 1 atmosphere pressure.

Saturated - the situation when a gas or liquid is filled to capacity with a certain substance. No additional amount of the same substance can be added under the given set of conditions.

Scrubber - a device used in the removal of pollutant gases from exhaust streams of combustion or industrial processes.

Scrubber train - a series of physical and/or chemical unit operations that remove pollutants from exhaust streams, carried out in a series of modules.

Slagging - scaling of precipitate or buildup of particulate material on equipment surfaces.

Spalling - the deterioration of stone, concrete, or ceramic materials because of chemical or physical action.

Stabilization - the addition of a flocculating agent to a wastewater to enhance the settling of solid materials.

Stabilization pond - a large excavation, usually manmade, for the storage and settling of stabilized sludge.

Stacked packings - ceramic, plastic, or wood materials placed in layers in a packed tower.

Standard conditions - a set of physical constants for the comparison of different gas volume flow rates. English = 60°F, 1 atmosphere pressure.

Stoichiometric ratio - a molar ratio of reactants in a chemical process; indicates to what extent lime is added to the reaction in excess of the theoretical amount required.

TPY - short tons per year; units used to express amounts of substances to be used or that are generated (usually solid materials such as coal or sludge).

Thickener - a continuous settling basin used to increase solids concentration from influent to underflow.

Underflow - concentrated solids flow from the bottom of a clarifier, scrubber, or thickener.

Utilization factor - ratio of hours an FGD system operated to hours in the given period, expressed as a percentage.

Venturi scrubber - an air pollution device used to accelerate concurrent liquid and gas flows for more turbulent and intimate contact.

WC - water column; units of pressure expressed as inches of water.

Weeping - the situation in an absorption tower when gas velocity is too low and does not provide for intimate contact between phases.